MQXF quench protection update

E. Ravaioli

with inputs from

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V. Marinozzi (INFN), T. Salmi (TUT),

B. Auchmann, J-P. Burnet, S. Izquierdo-Bermudez, F. Rodriguez-Mateos,
H. Prin, J. Rysti, E. Todesco, A. Verweij, D. Wollmann (CERN),

and many other CERN and LARP colleagues

Joint LARP CM26/Hi-Lumi Meeting at SLAC

19 May 2016

Outline

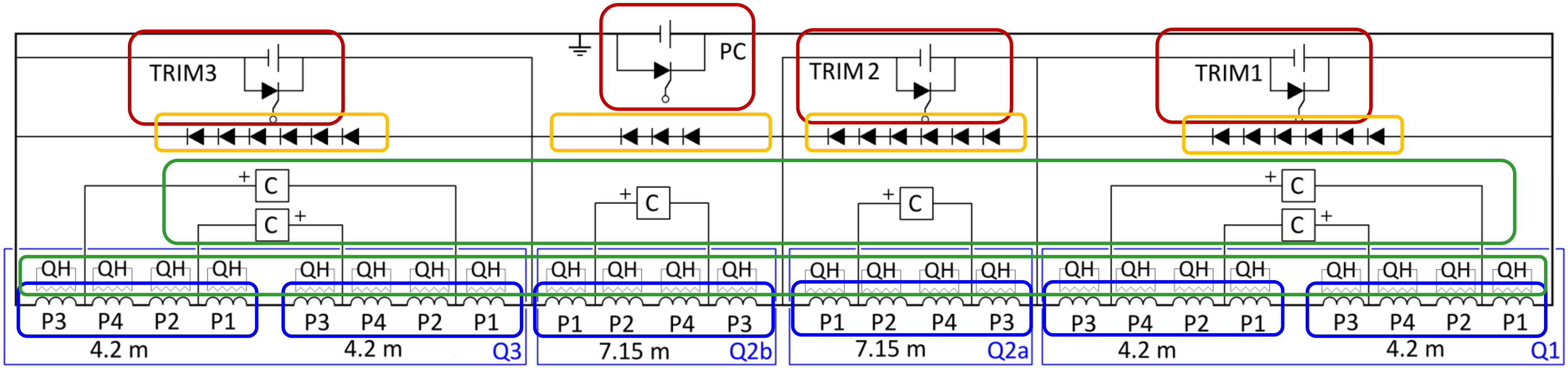
- Powering scheme and Quench protection system
  - Circuit analysis
  - CLIQ configuration
  - Quench heater connection scheme
  - Worst-case analysis
- Analysis of the MQXFS01 quench protection tests
  - Heater minimum power density to quench (G. Chlachidze)
  - Measured and simulated heater delays (G. Chlachidze, T. Salmi & S. Izquierdo-Bermudez, J. Rysti)
  - Dynamic effects during the decays (G. Chlachidze, V. Marinozzi)
  - Energy extraction decays
- Next steps & conclusions

Powering and Quench protection system

Following the
Conceptual Design Review of the Magnet Circuits for the HL-LHC
(CERN, 21-23 March 2016)

POWERING SYSTEM
1 main power supply (2-quadrant)
3 trim power supplies

Parallel Diodes



MAGNETS
4x 4.2 m QXF (LARP)
2x 7.15 m QXF (CERN)

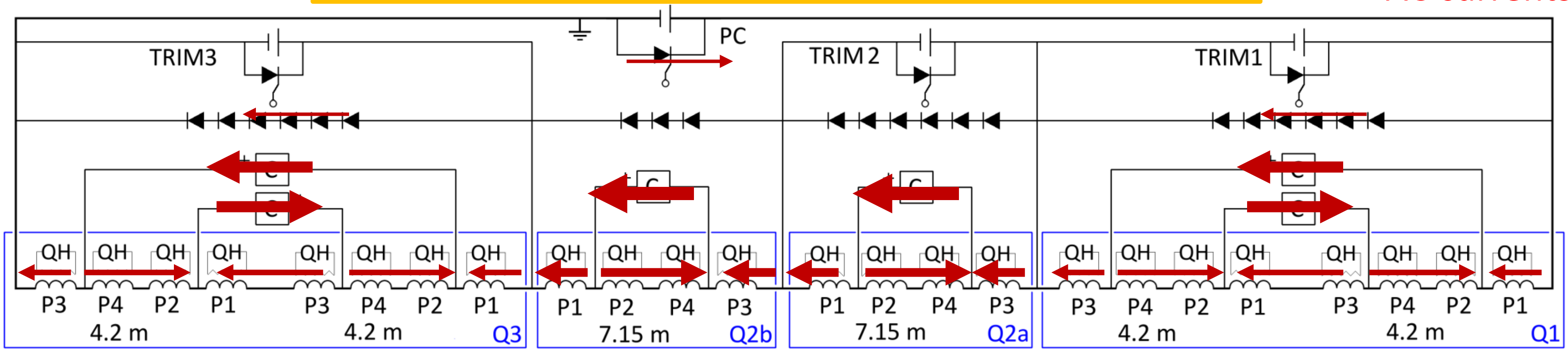
PROTECTION SYSTEM
CLIQ system + Quench Heater system

Quench protection system based on **quench heaters** and **CLIQ** is expected to provide the best solution for reducing hot-spot temperature and thermal stress, both in nominal and failure scenarios.

Circuit analysis

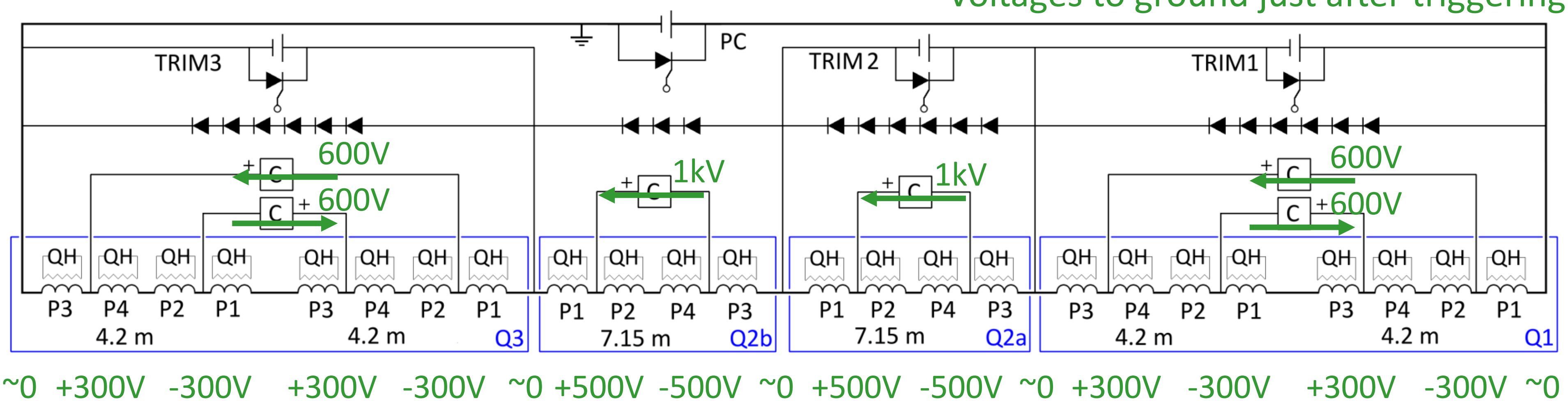
6 CLIQ units and 4 warm diode strings per triplet

AC currents

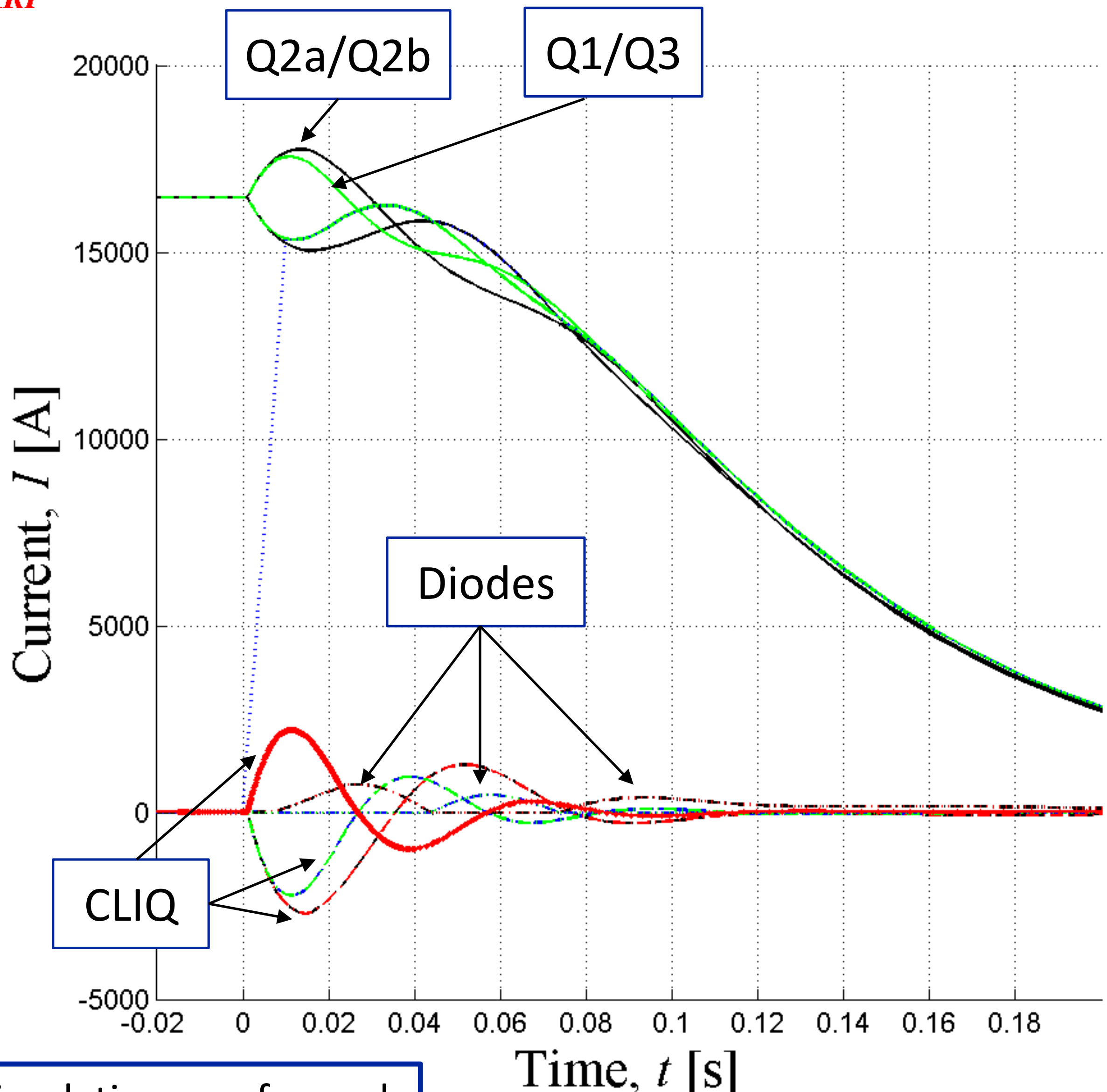


Parallel diodes only carry small current differences between magnets during the discharge

Voltages to ground just after triggering



Simulated currents in the circuit



Simulations performed with TALES

CLIQ units for Q2a/Q2b
Charging voltage: 1000 V
Capacitance: 40 mF

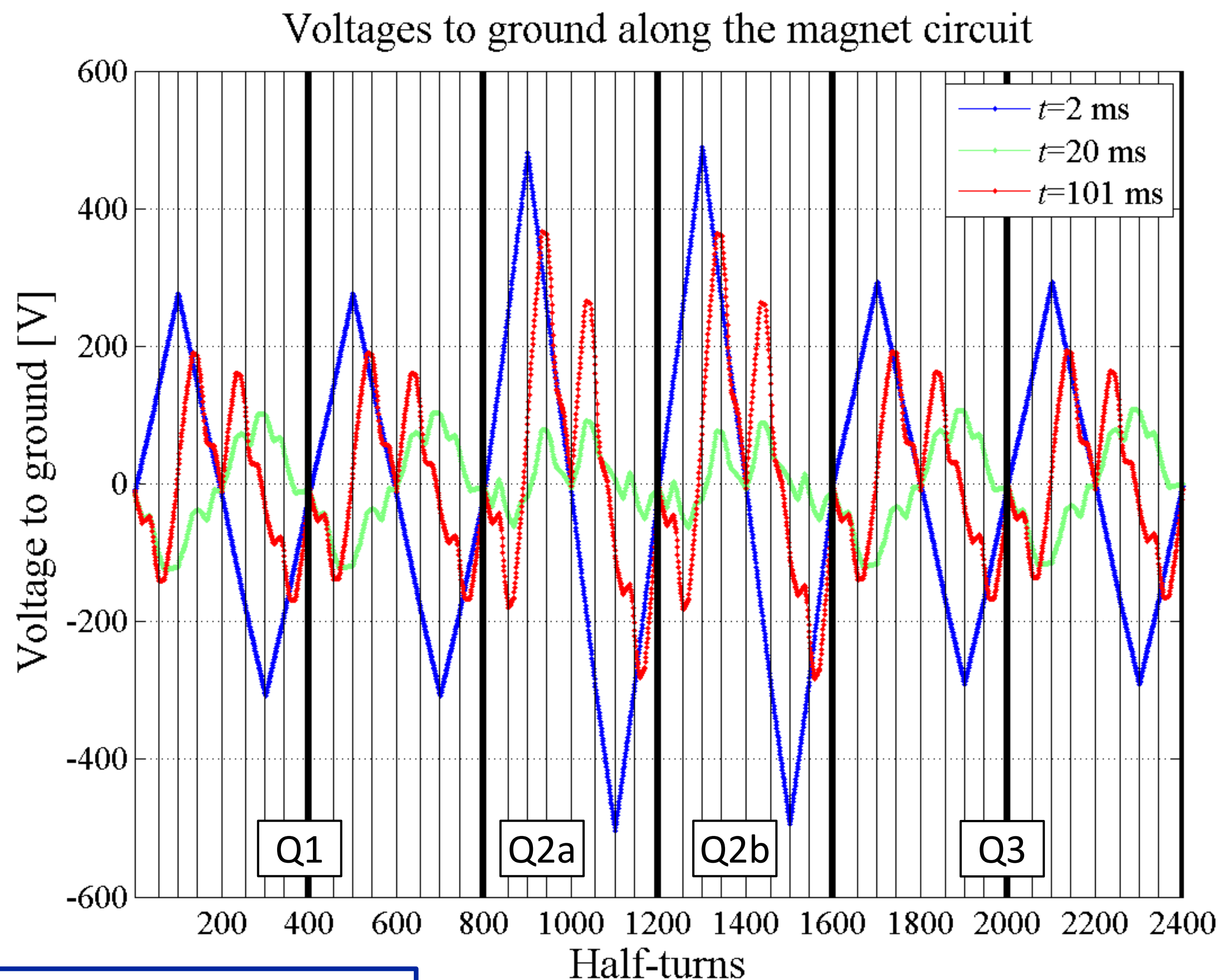
CLIQ units for Q1/Q3
Charging voltage: 600 V
Capacitance: 40 mF

Hot-spot temperature
T_{hot}~230 K

Currents through the SC Link
(no fault case)

- Main leads: Magnet current ± AC oscillations, 1.5 kA, 12 Hz
- Trim leads: Their initial current + AC pulse, 500 A, 12 Hz

Simulated voltages to ground

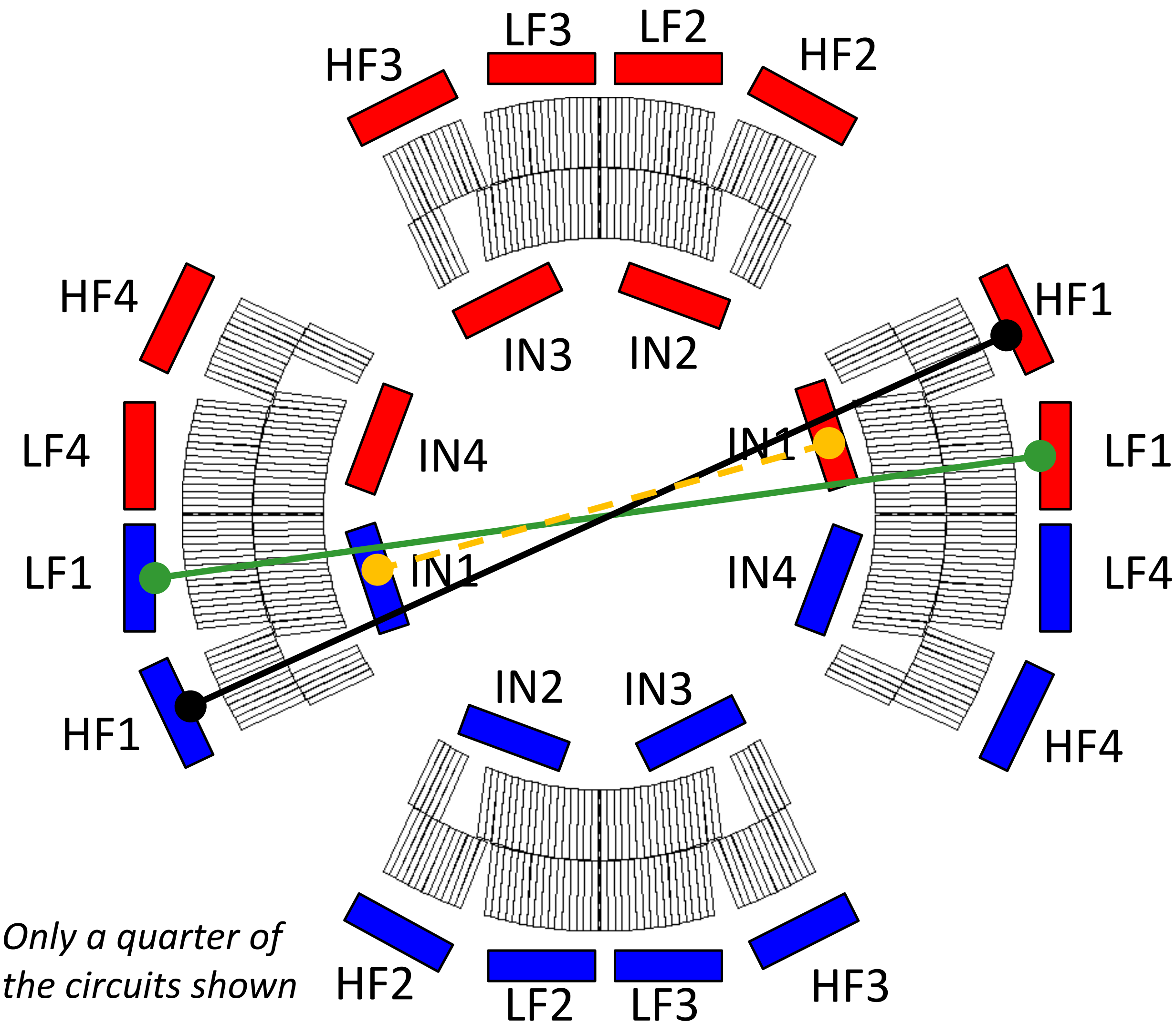


Voltages to ground and between coil sections in Q1/Q3 are 40% lower than Q2a/Q2b

Simulations performed with TALES

Proposed QH connection scheme

Each QH supply is connected to 2 strips in series



Only a quarter of the circuits shown

- Connection scheme that compensates the voltages induced by CLIQ and QH
- For inner quench heaters, option to power each strip individually (increased deposited power density, but more inner QH supplies needed, 4→8 per magnet)

Standard LHC quench heater power supply

Charging voltage: 900 V
Voltage to ground: ±450 V
Capacitance: 7.05 mF
Note: 2x 450 V, 14.1 mF modules in series

Worst-case analysis

The probability of particularly dangerous failure cases can be almost nullified by implementing the proposed mitigations.

In the remaining "realistic" failure cases, the worst-case analysis yields

	Q2a/Q2b (7.15 m)	Q1/Q3 (4.2 m)
Peak hot-spot temperature	320 K	320 K
Peak voltage to ground	520 V	430 V
Peak coil-to-QH voltage	520 V	430 V
Peak mid-plane voltage	500 V	400 V
Peak layer-to-layer voltage	500 V	340 V
Peak turn-to-turn voltage*	50 V	30 V

* Currently in the process of refining these values. Updated results expected soon.

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  - Measured and simulated heater delays (G. Chlachidze, T. Salmi & S. Izquierdo-Bermudez, J. Rysti)
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- Next steps & conclusions

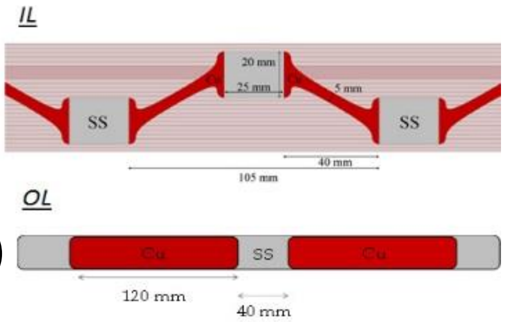
Minimum QH power density to quench

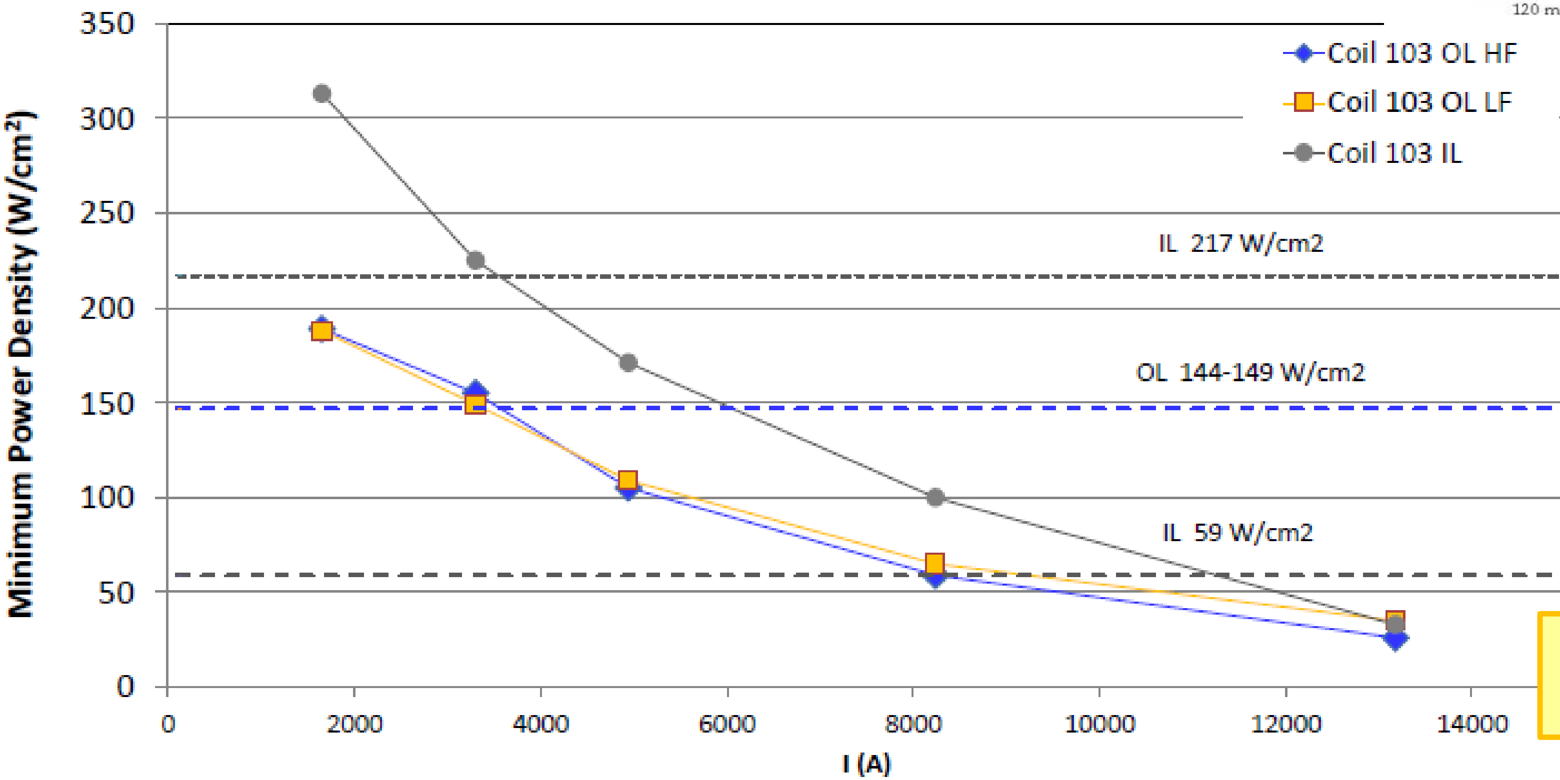
<u>CERN style heaters only</u>

Expected power density in 7 m long MQXF:

OL – 144-149 W/cm2 (2-strips in series per HFU)

IL – 59 W/cm2 (2-strips in series per HFU), 217 W/cm2 (1 strip per HFU)





C=19.2 mF

τ_{OL-LF}=23 ms

τ_{OL-HF}=21 ms

τ_{IL}=18 ms

G. Chlachidze (FNAL)

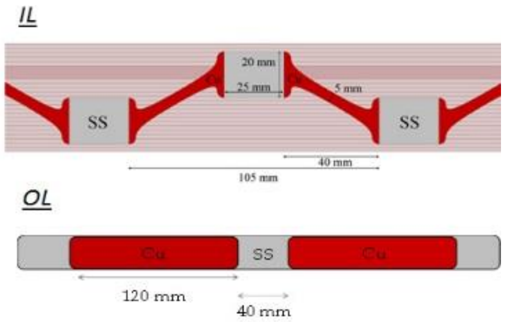
Minimum QH energy density to quench

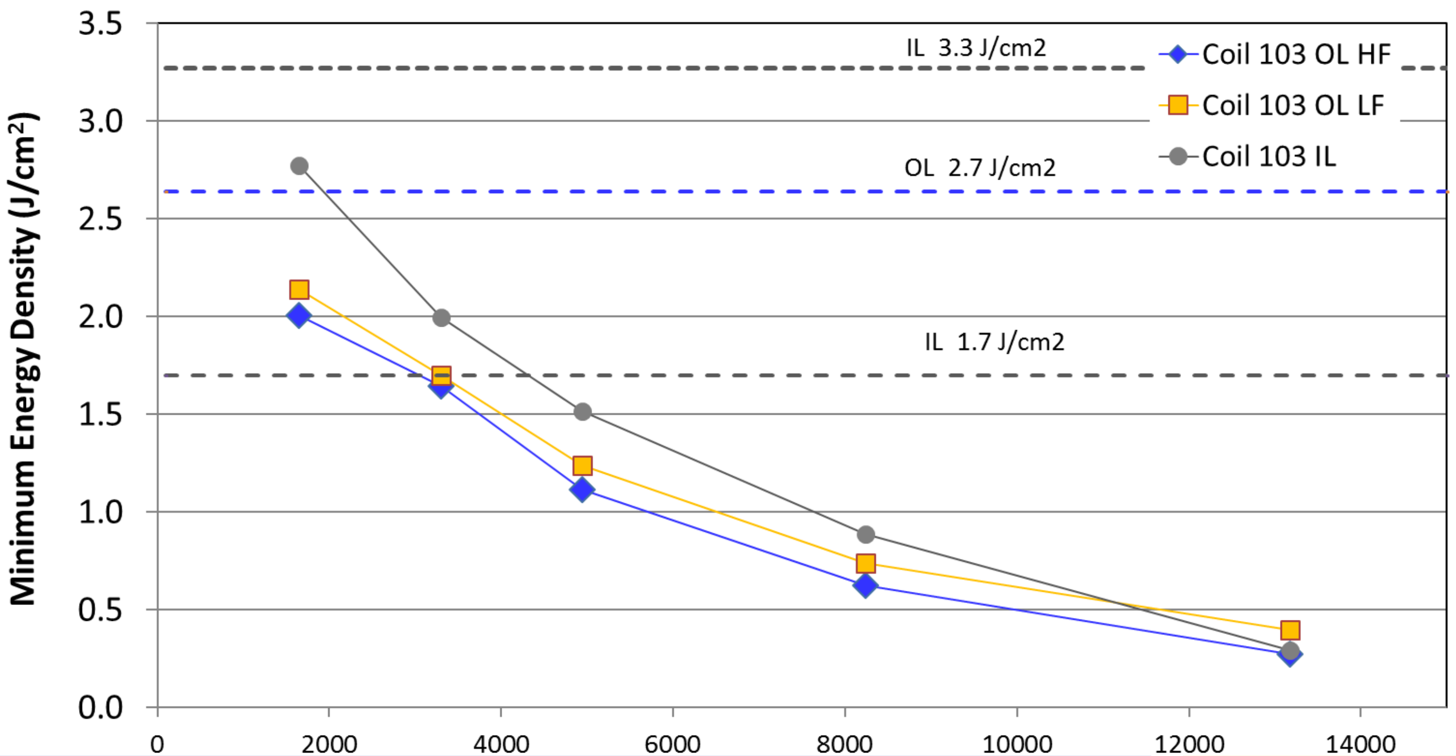
CERN style heaters only

Expected energy density in 7 m long MQXF:

OL – 2.6-2.7 J/cm2 (2-strips in series per HFU)

IL – 1.7 J/cm2 (2-strips in series per HFU), 3.3 J/cm2 (1 strip per HFU)



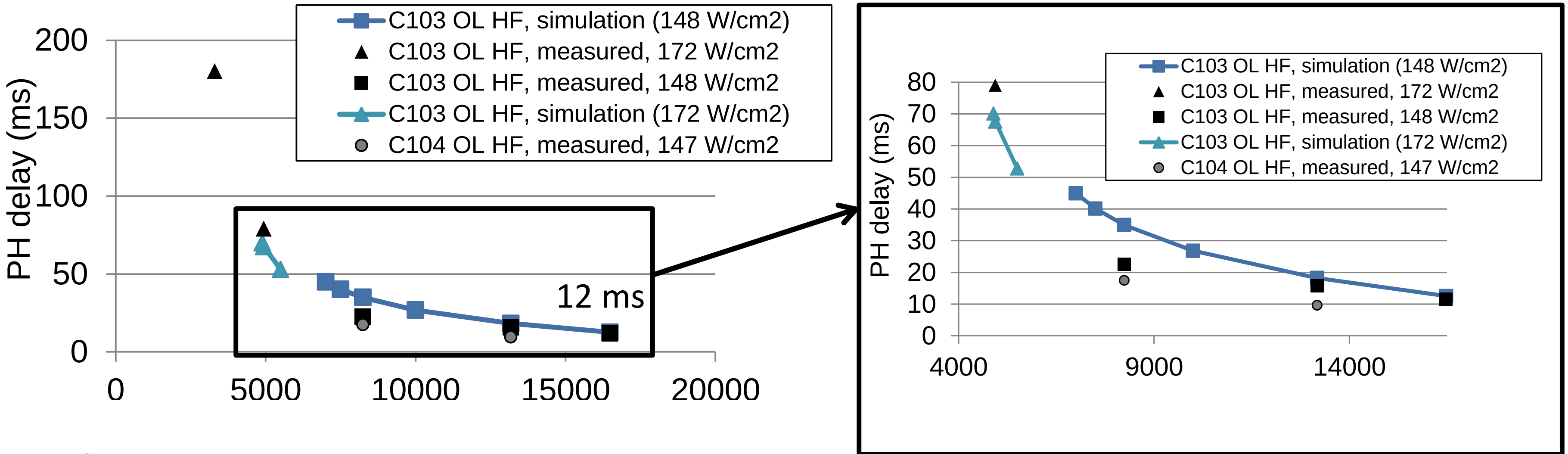


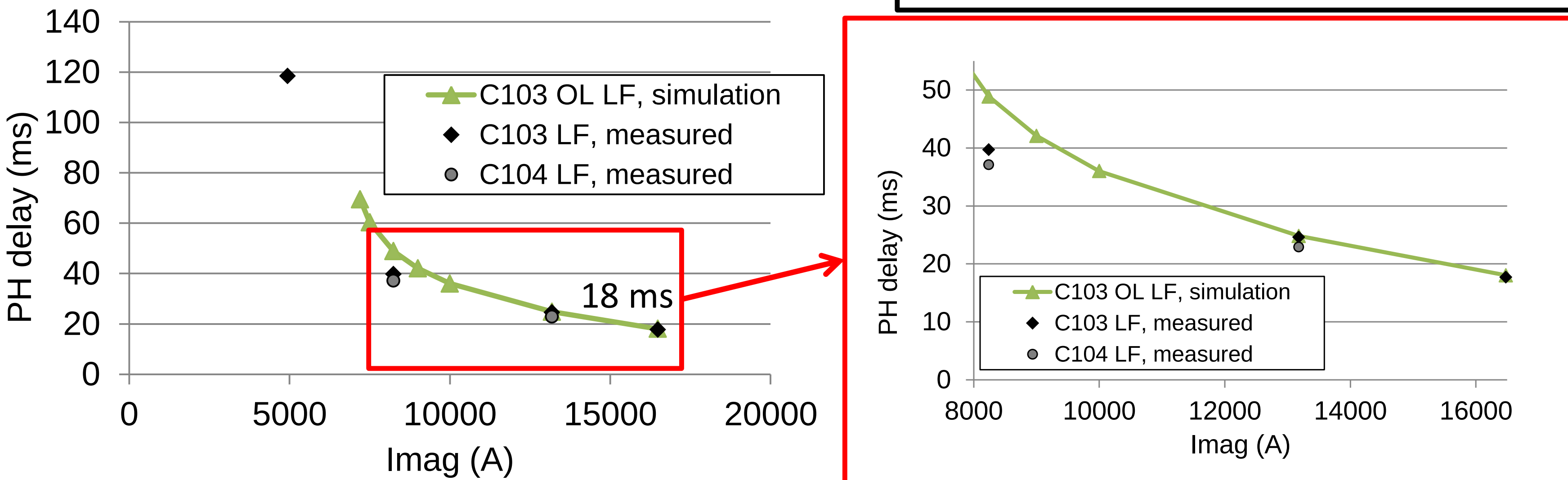
C=19.2 mF
τ_{OL-LF}=23 ms
τ_{OL-HF}=21 ms
τ_{IL}=18 ms

To further improve low-current performance, consider changing the QH strip design (longer heating stations) or use QH supplies with higher energy

Data: G. Chlachidze
Analysis: S. Izquierdo-Bermudez, E. Ravaioli, J. Rysti

Measured and simulated heater delays – Outer layer



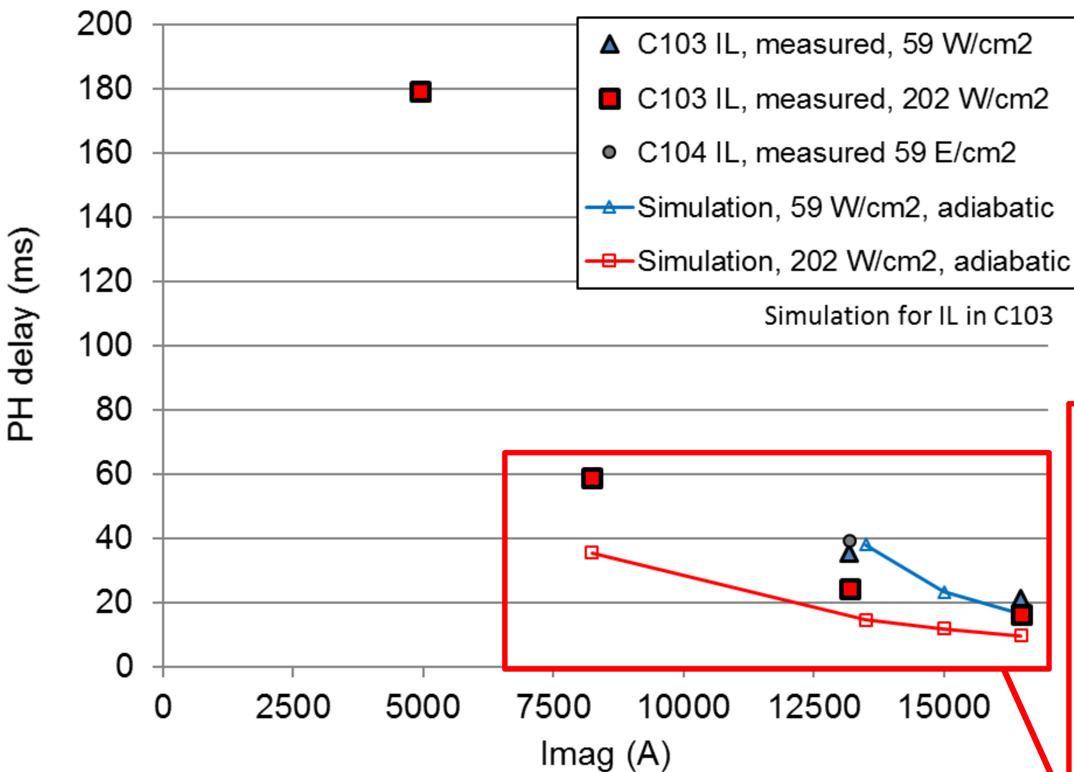


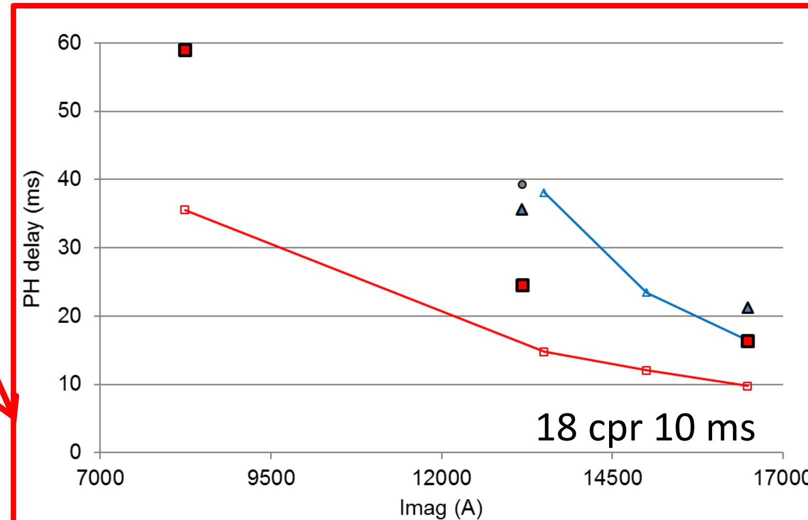
Data: G. Chlachidze (FNAL)
Simulations: T. Salmi (TUT)

Simulations performed with CoHDA

Measured and simulated heater delays – Inner layer

MQXFS01 stainless-steel only IL heaters not yet tested

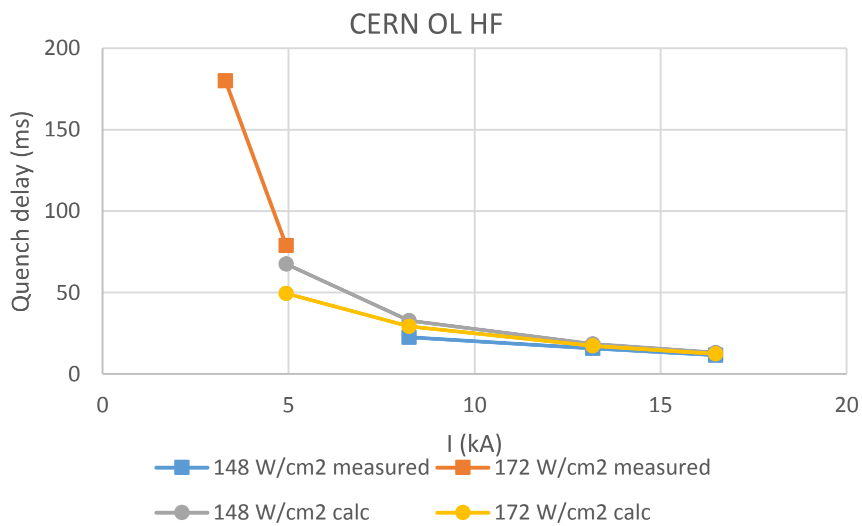


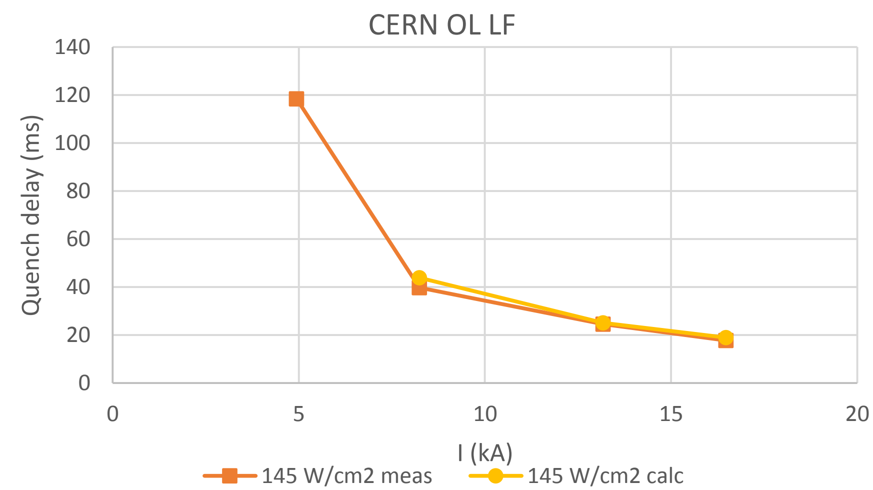


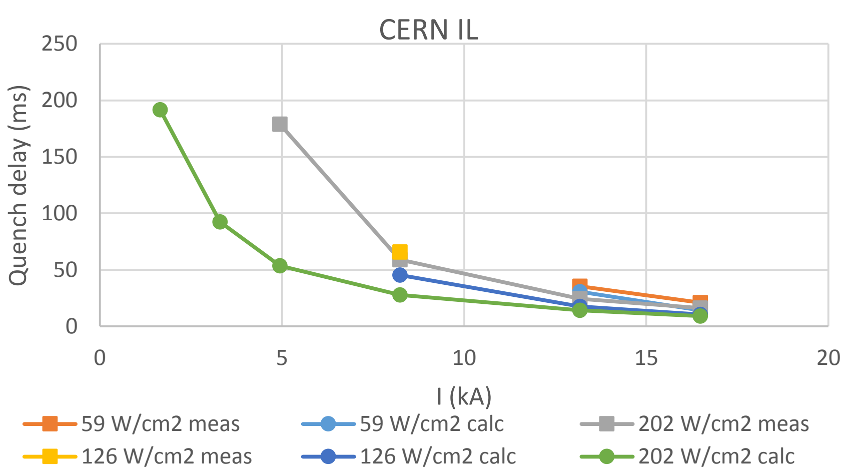
Data: G. Chlachidze (FNAL)
Simulations: T. Salmi (TUT)

Simulations performed with CoHDA

Measured and simulated heater delays – Outer and inner layers







OL heaters: Very nice agreement between measurements and simulations from two independent models

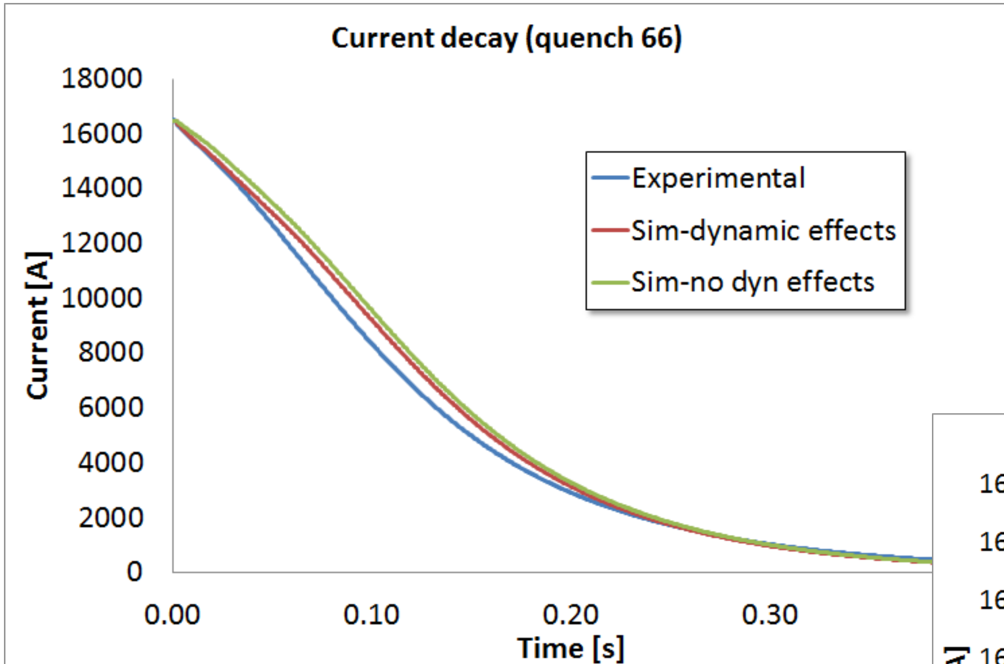
IL heaters: Both independent models predict shorter delays at nominal current. Further analysis required

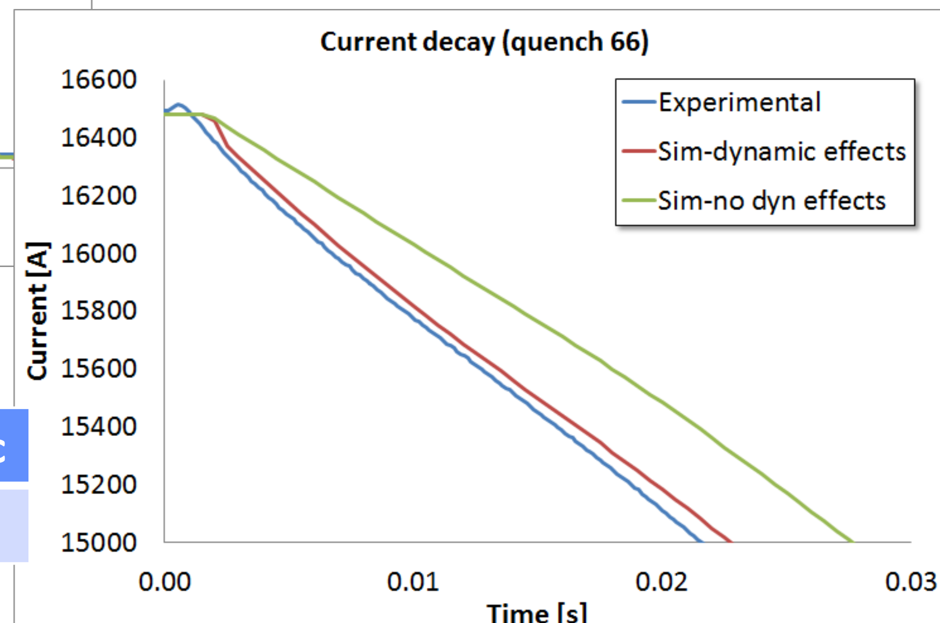
Additional heater delay tests with added warm resistance foreseen in the coming weeks

Data: G. Chlachidze (FNAL)
Simulations: J. Rysti (CERN)

Simulations performed with Comsol

Measured and simulated decays – Dynamic effects





Quench load [MA^{2}s]

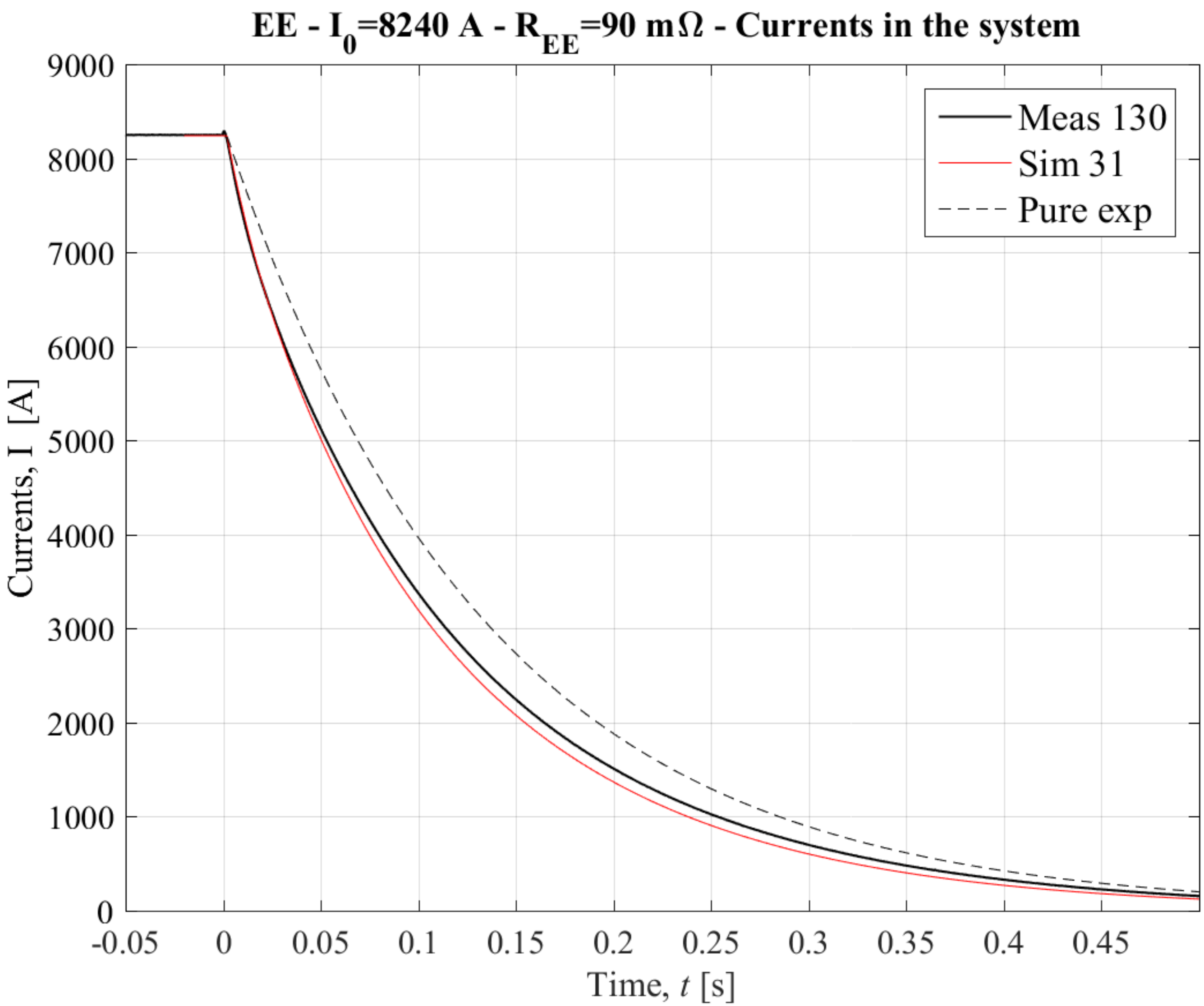
Experimental	Sim-dynamic	Sim-no dynamic
19.8	22.4	23.8

Data: G. Chlachidze (FNAL)
Simulations: V. Marinozzi (INFN)

Simulations performed with QLASA

Preliminary results

Energy extraction decays (no heaters)



I_0=8.24 kA
R_{EE}=90 mΩ

Data: G. Chlachidze (FNAL)

Simulations performed with LEDET

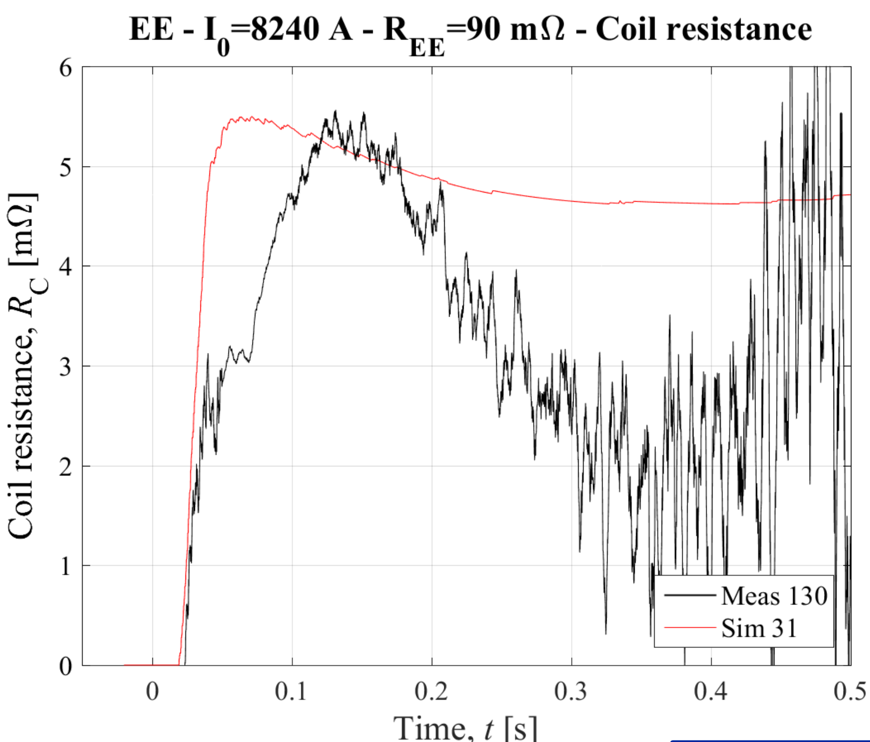
Energy extraction decays (no heaters) Quench back and inductance reduction

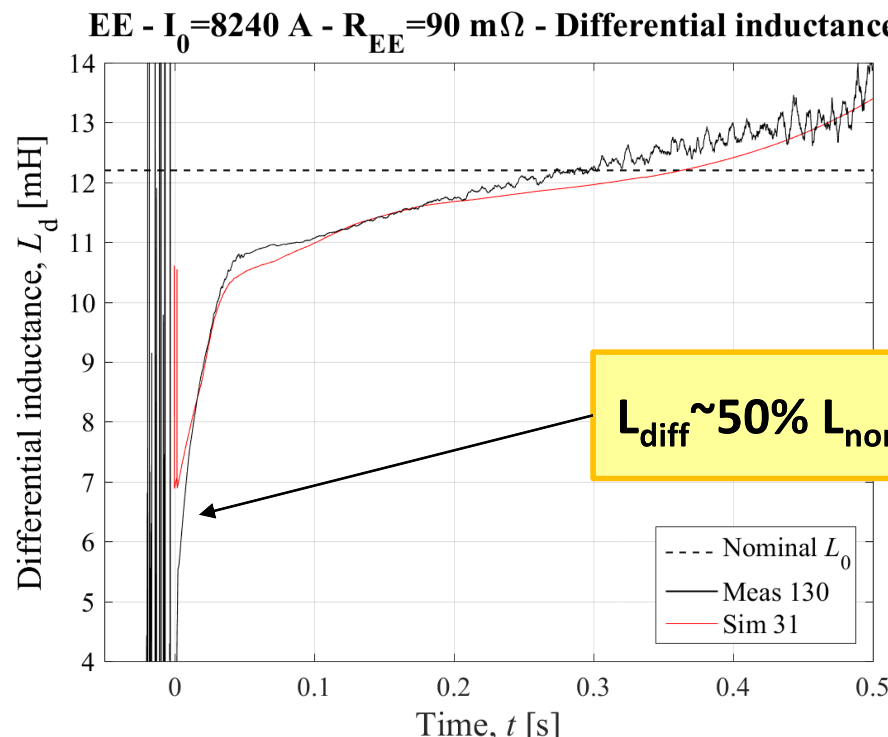
LARP

High Luminosity LHC

I_0=8.24 kA
R_{EE}=90 mΩ

L_{diff}~50% L_{nom} R_{coil}~5 mΩ → The faster decay observed in this discharge is mainly due to a reduction of the inductance, not due to quench-back





L_{diff}~50% L_{nom}

Data: G. Chlachidze (FNAL)

Simulations performed with LEDET

Next steps & conclusions

Circuit design

Heater delay tests

Energy extraction tests (strand parameters)

Validation of independent models

<u>Summer 2016 testing campaigns</u>
(MQXFS1b, MQXFS2, Long mirror)

Quench integral studies (no energy extraction)

CLIQ performance

Additional heater delay tests

<u>Final heater design</u>
Circuits, Strip design, Supplies

<u>Final CLIQ design</u>
Capacitance, Charging voltage

Reliability studies

<u>Conclusions</u>

- Improved confidence and validation of independent simulation tools
- <u>Next test campaign critical for the definition of the parameters of the integrated quench protection system (heaters and CLIQ)</u>

<u>Targeted improvements</u>

- Assure the effectiveness of the quench heaters below 3 kA
- Achieve faster response time of the inner-layer quench heaters
- Test performance of stainless-steel only IL heaters

Annex

<u>Here you'll find</u>:

- Additional information about the circuit (slides 20-23)
- Criteria for the powering and protection design choices (slides 24-27)
- Simulated currents, voltages to ground, hot-spot temperature (slides 28-31)
- Requirements on CLIQ terminals and leads – to be updated (slide 32)
- Proposed electrical schemes for CLIQ tests (slide 33)
- Superposition of CLIQ and QH induced voltages (slides 34-36)
- Simulations of failure cases (slides 37-50)
- Tables of characteristic voltages in failure cases (slides 51-56)
- First redundancy studies (slides 57-58)
- Hot-spot temperature and temperature distribution for various protection system options (slides 59-60)
- Reason why parallel elements are needed in the circuit (slides 61-62)
- What is CLIQ (slide 63)
- Quick way to tell if a CLIQ configuration is optimized for MQXF or not (slides 64-65)
- Influence of an energy-extraction system (slide 66)

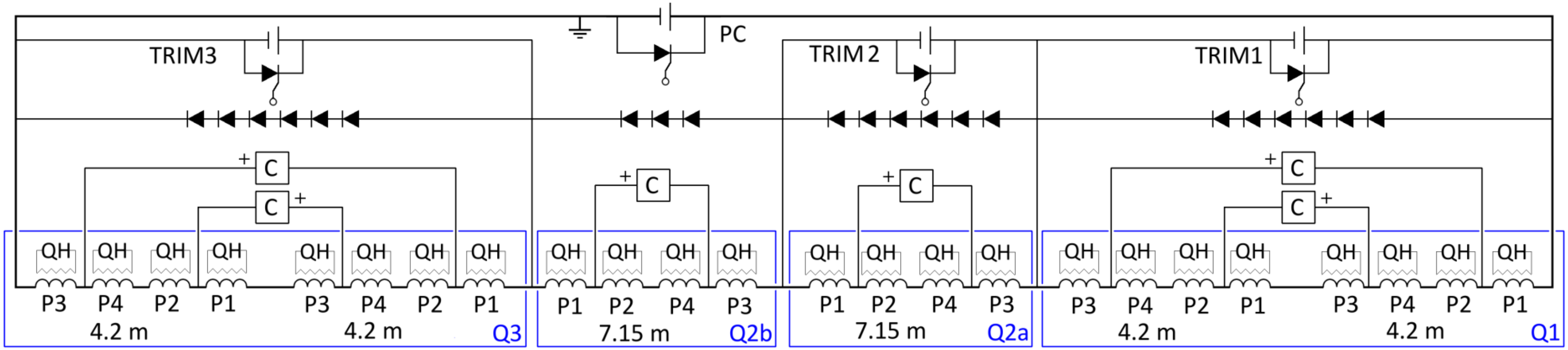
Notes

When not specified:

- The powering scheme includes **one power supply** (less expensive, more challenging)
- **EE** system is **not present**
- **QH** attached to the outer layer of the coil (2 circuits per pole) but not to the inner layer

- Current level set to the **nominal current** (I_0=16.47 kA)
- Each **CLIQ** unit has a capacitance C=40 mF charged to U_0=1 kV
- Each **QH** system has 8 circuits, each with a capacitance 9.6 mF charged to ±450 V (Q1/Q3) or ±300 V (Q2a/Q2b)

Powering and Quench protection system

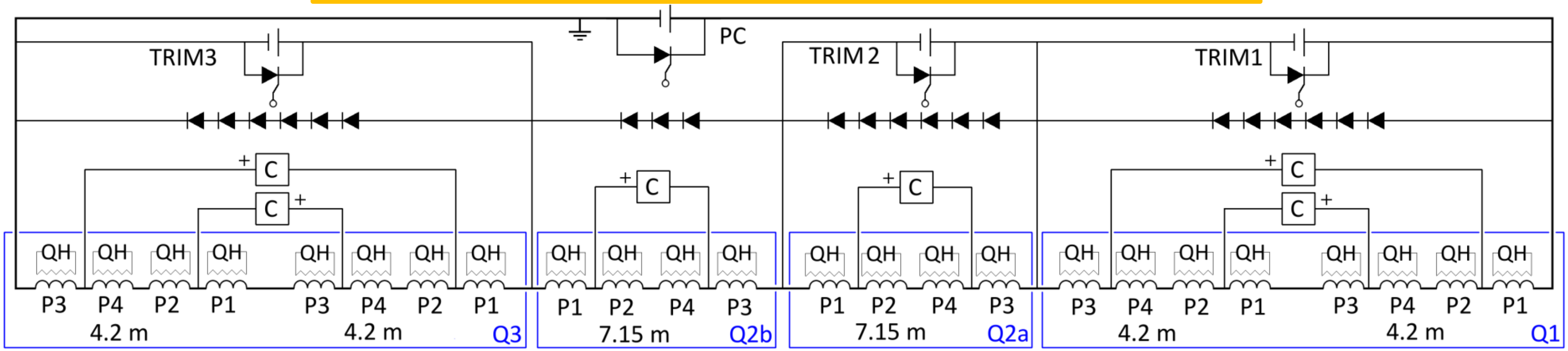


This is a conceptual diagram. The actual electrical order and connection scheme of the poles of each magnet will depend on several factors:

- Opposite field orientation required for Q1/Q3 versus Q2a/Q2b
- Naming of the poles based on the physical position they occupy (with respect to the lead end? to the interaction point?)
- Pizza box design
- Rotation of the coil around its axis
- Positioning of the lead ends of each magnet

CLIQ system

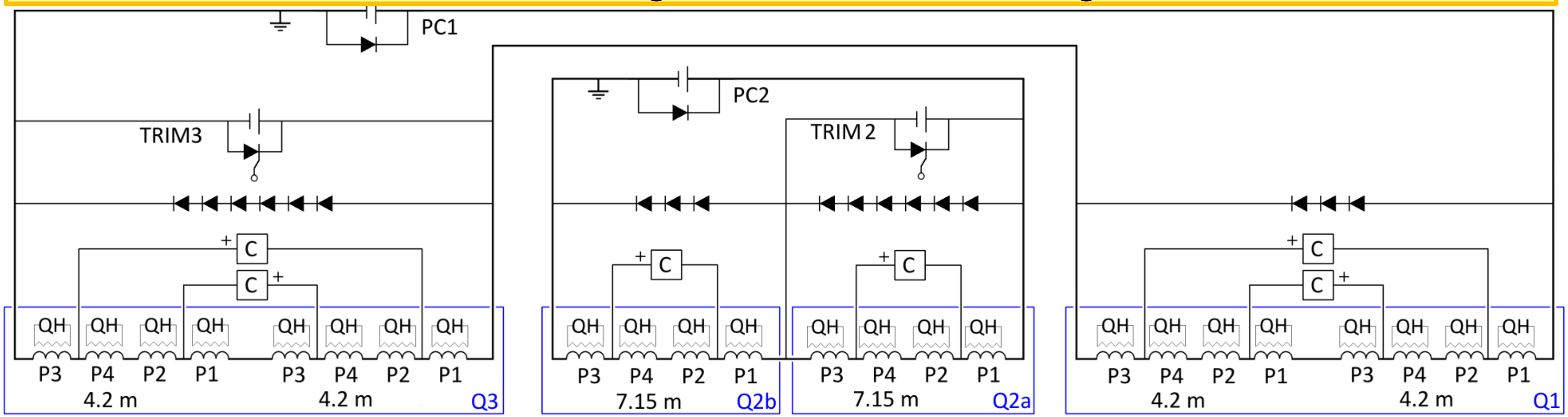
6 CLIQ units and 4 warm diode strings per triplet



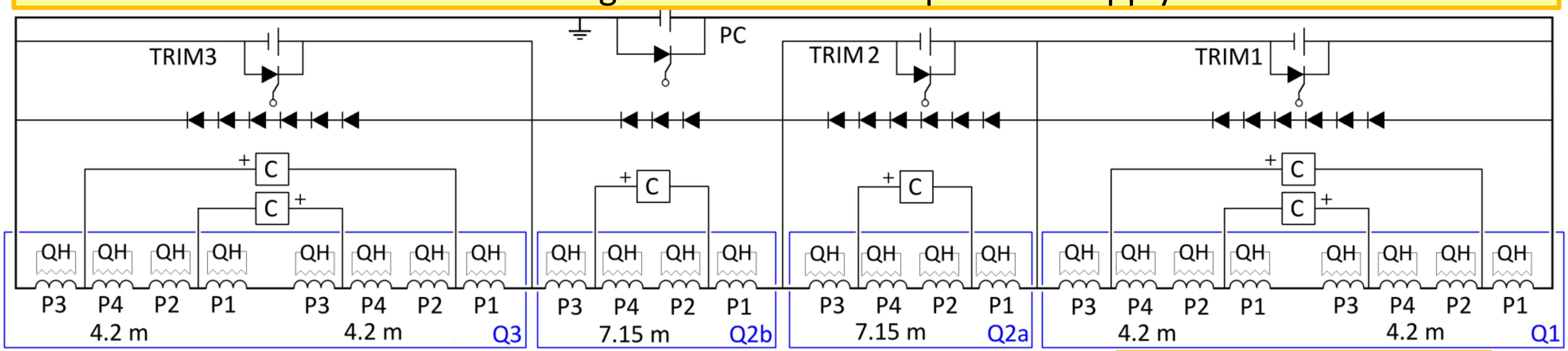
- The proposed connection scheme of 2 units to Q1/Q3 greatly reduces the peak voltage to ground in the case of misfiring of one CLIQ unit
- Additional current lead between the 2 magnets of Q1/Q3 not needed
- All parallel elements can be installed to the leads already foreseen for the trim power supplies
- Polarities of the CLIQ units is a key ingredient! (QA, testing at 50 V)
- All CLIQ units have the same capacitance (easier to design, manufacture, maintain the units). Units connected to Q1/Q3 can be charged to a lower voltage (600 V)
- Warm diodes are preferred over resistors (no leakage current during ramps, better control of the voltages to ground in failure cases)

Powering schemes

Baseline: Two main 1-quadrant power supplies + 2 trim power supplies
Slow discharge with free-wheel discharge



One main 2-quadrant power supplies + 3 trim power supplies
Slow discharge achieved with 2-quadrant supply



Little impact on magnet protection!

1 or 2 circuits – Advantages

	1 Circuit		2 Circuits	
Criterion	**Fulfilment**	**Advantages**	**Fulfilment**	**Advantages**
Protection	1		1	• Lower stored energy per circuit
Compatibility	0.8	• Less effect of power converter ripples on beams as compensated. • Faster ramp down (2 Quadrant PC)	0.8	
Reliability	0.7	• Less electromagnetic interference.	0.8	• Reduced # of high current quenches. • Better distribution of voltage to ground during quench (without parallel elements).
Availability	0.8	• Less high current power converters & links → less beam aborts	0.7	• Quicker quench recovery (firing of heaters in less magnets).
Maintainability	0.8	• Less high current power converters & links	0.6	
Simplicity	0.7	• Less high current leads.	0.6	• Only two trim circuits.
Cost saving	1	• 1 main power converter (but 3 trims). • Less high current leads + less splices. • Reduced operational costs	0.7	
Space Saving	1	• 1 main power converter (but 3 trims). • Less high current leads. • 2 Quadrant power converters save space (less warm cables needed)	0.6	

Judgment of fulfillment [0…1], subjective and open for discussions

Options for the quench protection

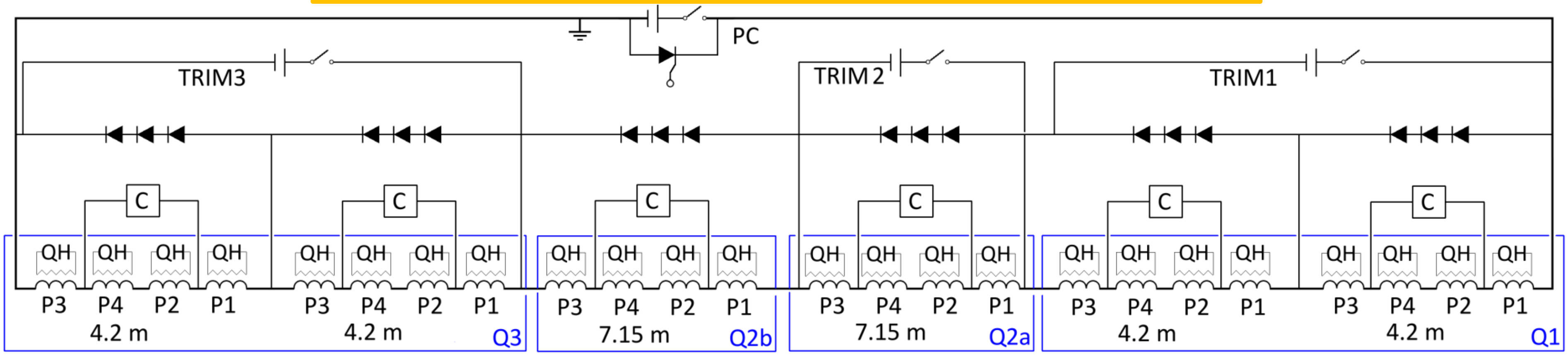
	CLIQ + Outer QH (+Inner QH?)		Outer QH + Inner QH	
Criterion	Fulfillment	Features	Features	Fulfillment
Protection	1	Hot-spot temperature <300 K and peak voltage to ground <500 V in all realistic failure cases analyzed		0.9
Compatibility	1	Less dependence on magnet/cable/strand parameters		0.9
Reliability	1	Higher redundancy No expected performance degradation More homogeneous temperature distribution in the coil windings	Lower characteristic voltages (in absence of failures) Some concern on long-term inner QH performance	0.75
Availability	0.9 (0.8)	1 CLIQ and 8(+4) QH supplies per magnet [Option to rely on less QH power supplies increasing availability at the cost of redundancy]	8+4 QH supplies per magnet	0.9
Maintainability	1	Very easy repair/replacement of damaged CLIQ units (room temperature operation)		0.9
Simplicity	0.9	Less dependence on magnet/cable/strand parameters	R&D needed for Inner QH technology Easier modelling	0.9
Cost saving	0.9 (0.8)	1 CLIQ and 8(+4) QH supplies per magnet	8+4 QH supplies per magnet	0.9
Space Saving	0.9 (0.8)	1 CLIQ and 8(+4) QH supplies per magnet	8+4 QH supplies per magnet	0.9

Options for CLIQ configuration

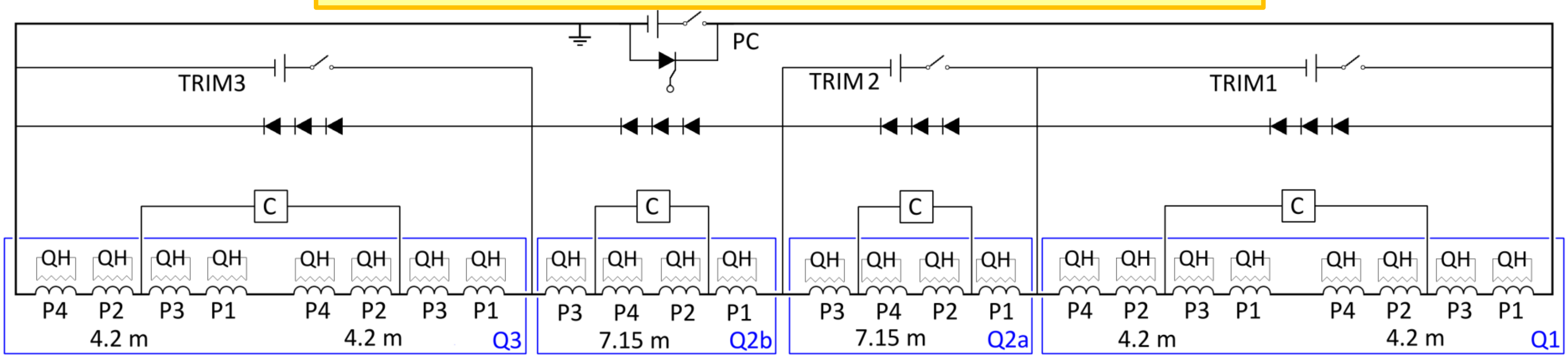
	6-CLIQ, 4 Warm Diodes		4-CLIQ, 4 Warm Diodes	
Criterion	Fulfill ment	Advantages	Advantages	Fulfillm ent
Protection	1	Both options assure hot-spot temperature <300 K and peak voltage to ground <500 V in all realistic failure cases analyzed		1
Compatibility	1	Both options use identical CLIQ units for all magnets		1
Reliability	1	Reduces voltages to ground and between coil sections in Q1/Q3 by 40%		0.85
Availability	0.9		4 CLIQ units per triplet circuit instead of 6	1
Maintainability	0.9		4 CLIQ units per triplet circuit instead of 6	1
Simplicity	0.9	Same pole electrical order and similar CLIQ connection scheme for short and long magnets. CLIQ performance can be tested in machine-relevant configuration more easily.	4 CLIQ units per triplet circuit instead of 6	0.7
Cost saving	0.9	No need to redesign the pizza box of Q1/Q3	4 CLIQ units per triplet circuit instead of 6	0.9
Space Saving	0.9		4 CLIQ units per triplet circuit instead of 6	1

CLIQ configuration -1

6 CLIQ units and 6 warm diode strings per triplet

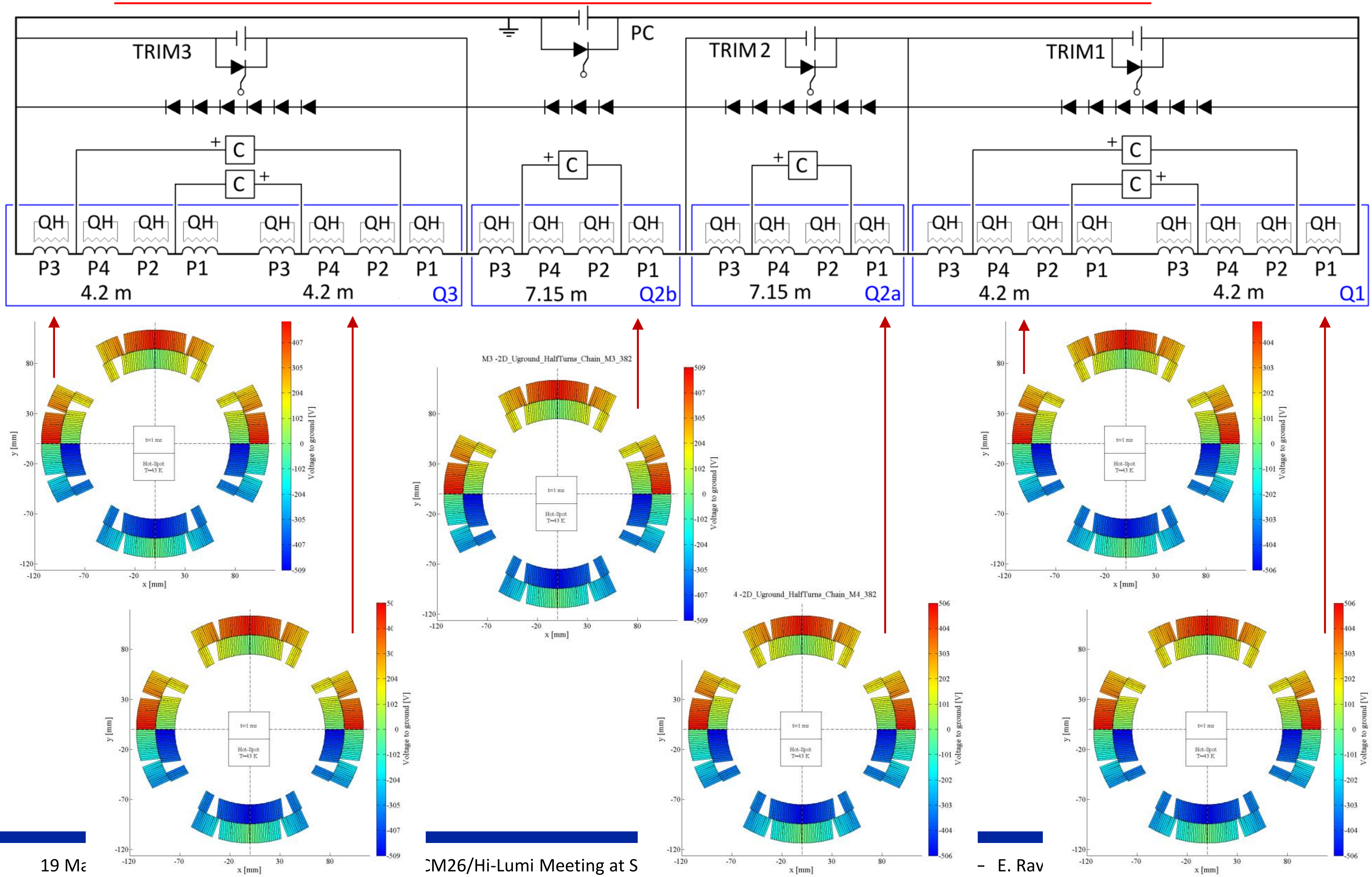


4 CLIQ units and 4 warm diode strings per triplet



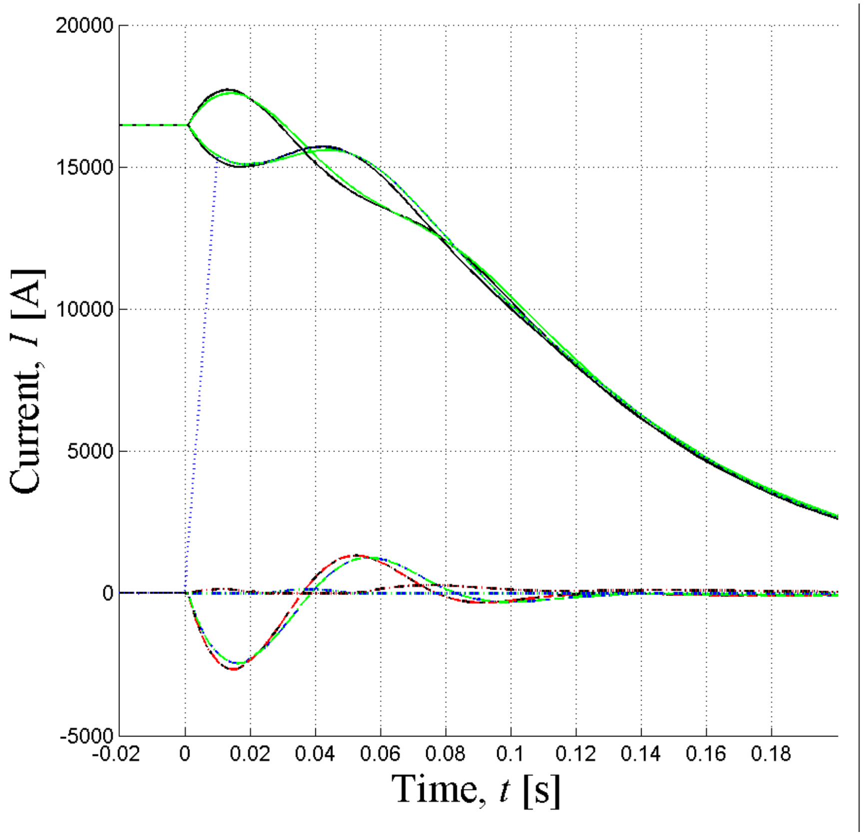
Less CLIQ units, parallel elements, parallel leads. But change of the electrical order of Q1/Q3 required, and peak voltages to ground in Q1/Q3 increased.

What are the expected voltages during a discharge?

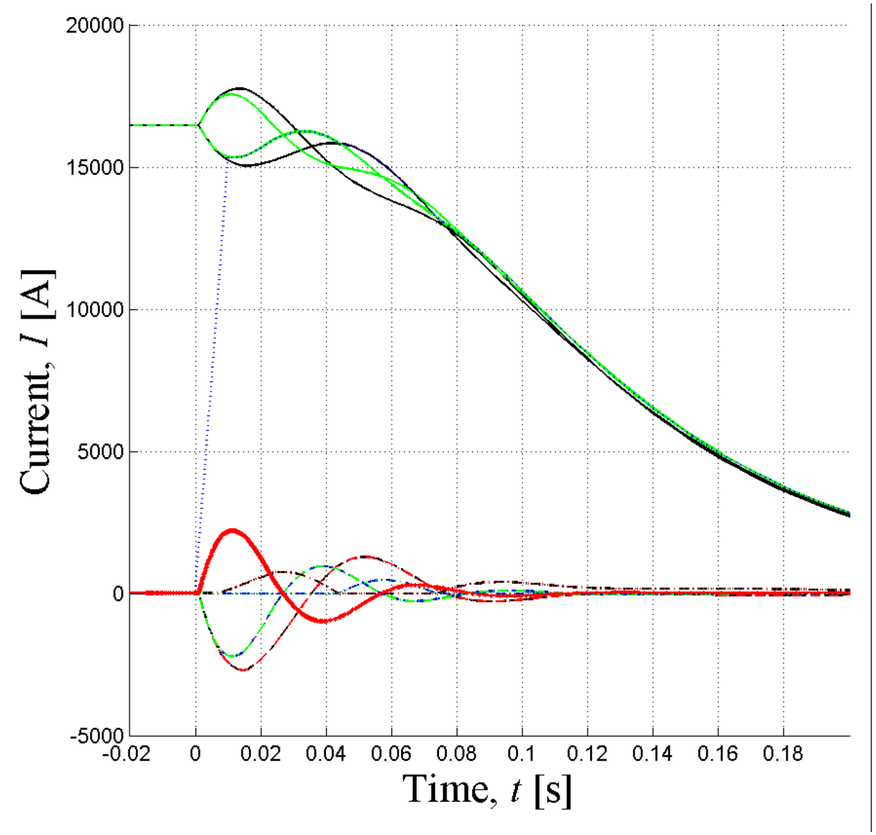


Simulated currents in the circuit

4-CLIQ
4 Warm Diodes



6-CLIQ
4 Warm Diodes



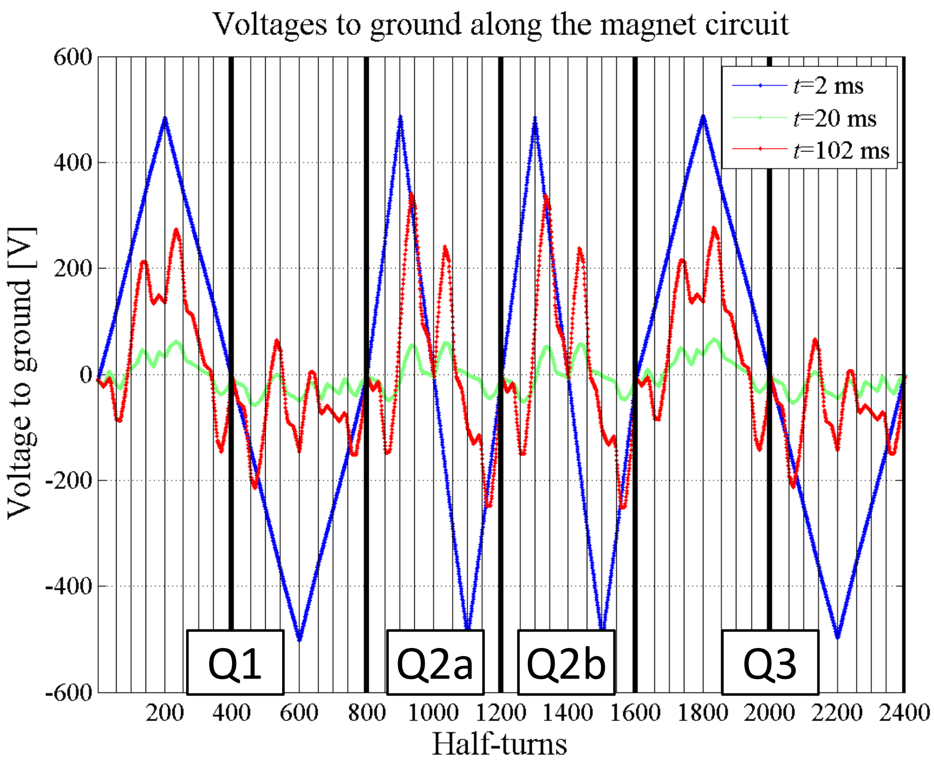
Negligible difference in the hot-spot temperature (T_{hot}~230 K)

Simulated voltages to ground

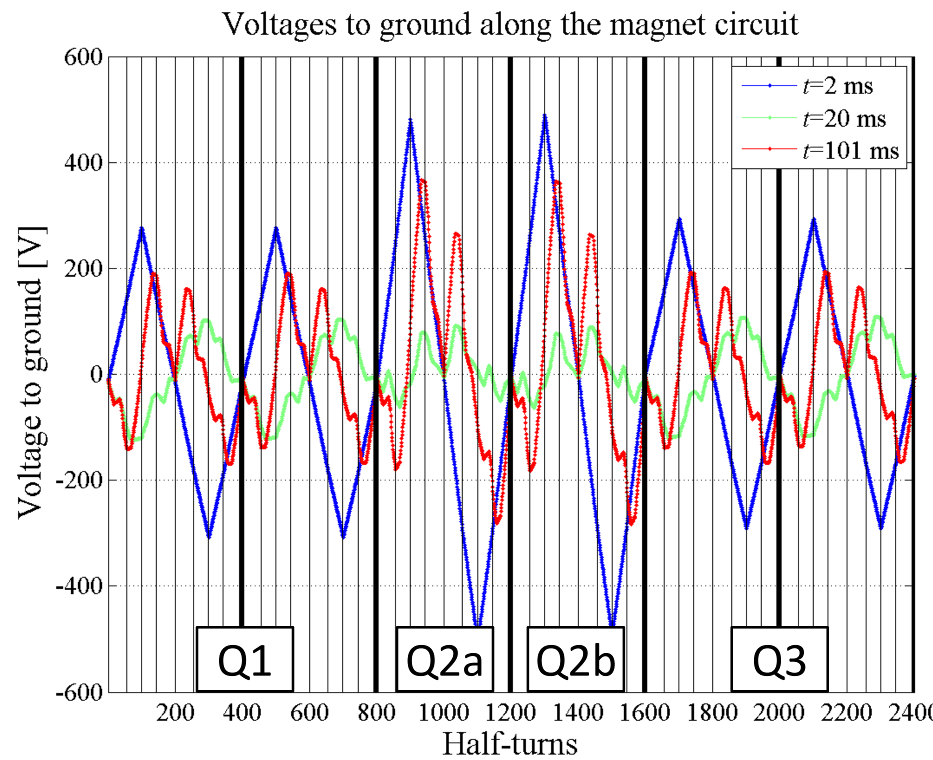
LARP

High Luminosity LHC

4-CLIQ
4 Warm Diodes



6-CLIQ
4 Warm Diodes



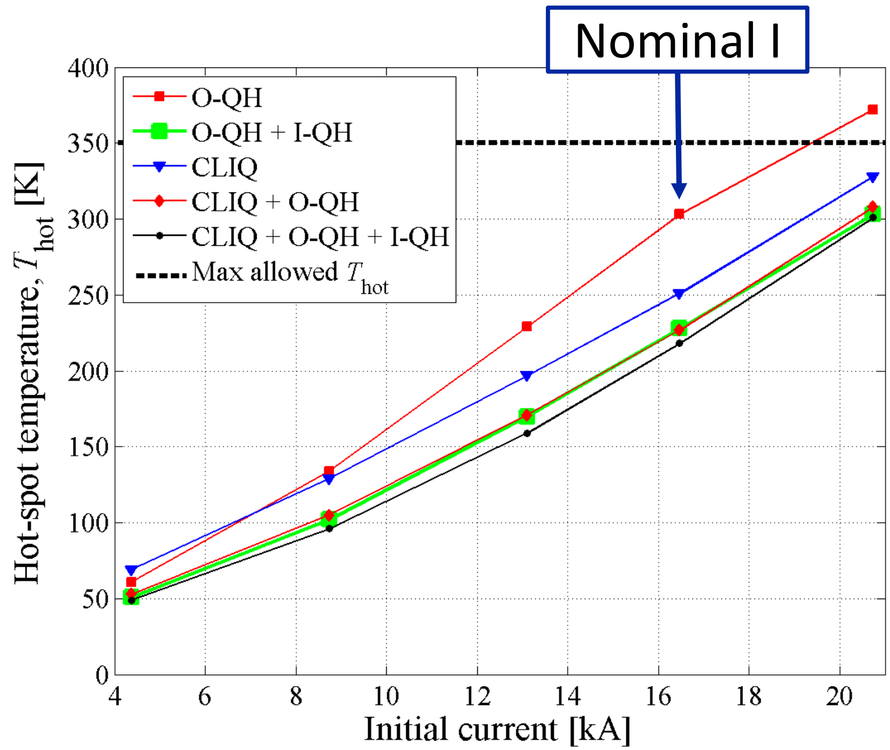
Reduced voltages to ground and between coil sections in Q1/Q3 by 40%

Simulated hot-spot temperature

CLIQ		Y	Y	N	N	N
OL heaters		Y	Y	Y	3/4 strips	2/4 strips
IL heaters		Y	N	N	N	N
Hot-spot Temp.	K	216	210-231	303-	325-366	322-363
Coil-Ground	V	510	510	290-470	460-680	690-950
Turn-Turn	V	30	35	53-61	64-75	72-88
			**	*	*	*

*Note1: QH simulations performed with and without quench-back and dynamic inductance effects, and assuming QH are triggered 1ms after detection/validation (present value is 5ms)

**Note2: CLIQ+QH simulations performed varying in a wide range the cable/strand parameters

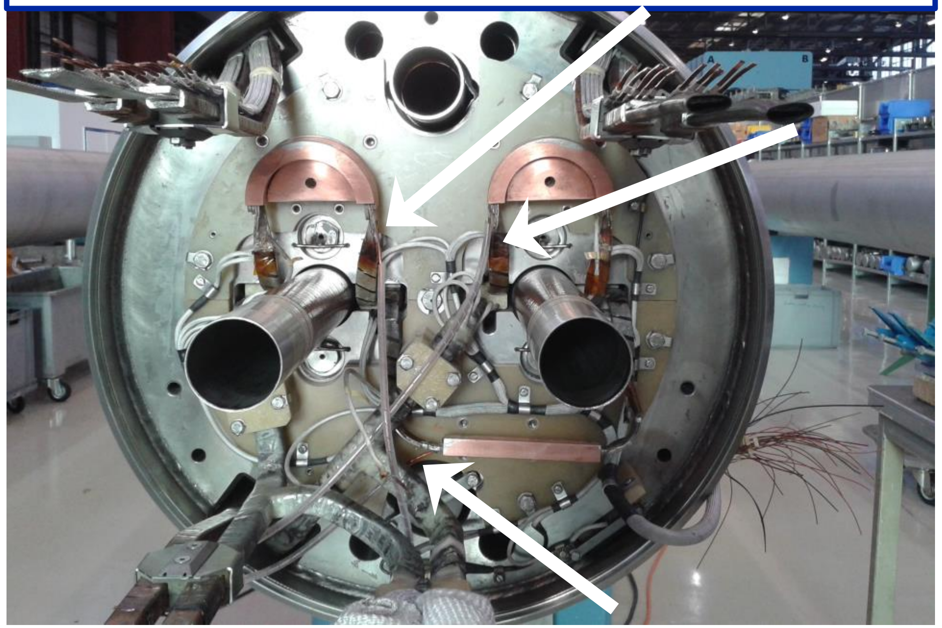


CLIQ + QH's seems the best compromise for reducing hot-spot temperature and thermal stress, and increasing redundancy and robustness.

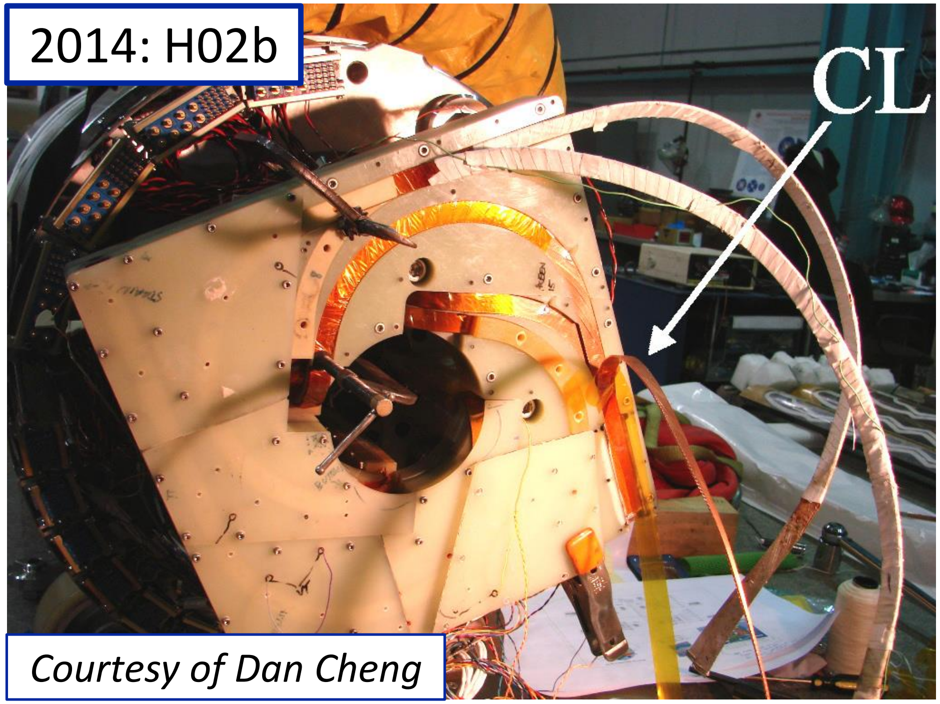
What are the requirements for the CLIQ terminal and leads?

- Leads attached to the coils: Copper cross-section >10 mm2, RRR>100
- Superconducting lead preferred to further reduce its resistance
- Leads outside the cryostat: If the units are located relatively far from the magnet area (80 m?), larger cross-section needed
- Target: Overall resistance of a CLIQ discharge system (external leads + internal resistance of the unit) < 10 mΩ

Aug 2015: full-size 15 m LHC main dipole



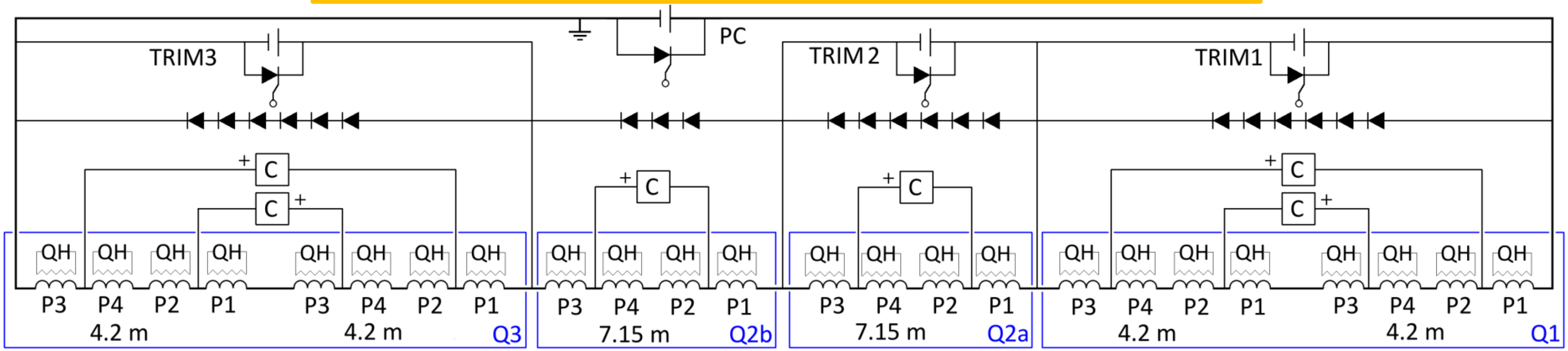
2014: H02b



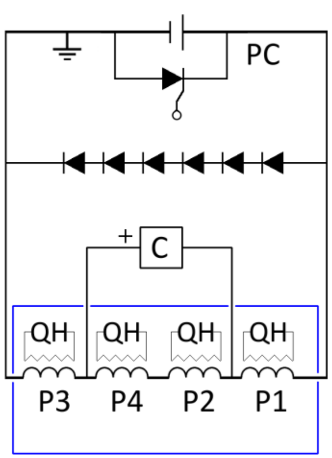
Courtesy of Dan Cheng

Test of magnets and cold masses

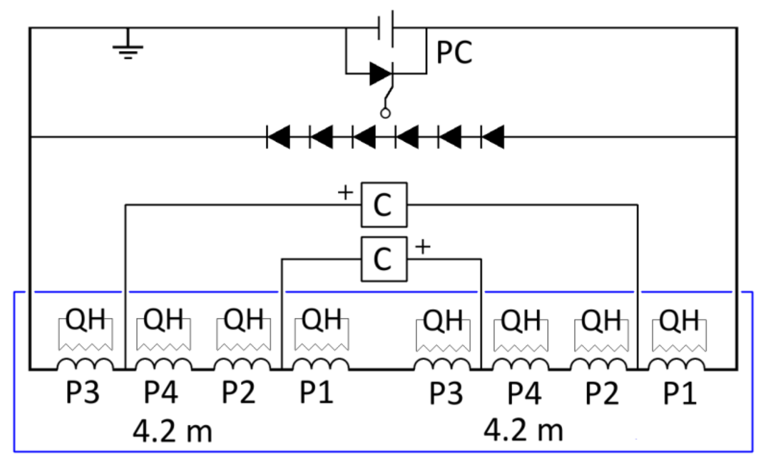
6 CLIQ units and 4 warm diode strings per triplet



Magnet test (7.15 or 4.2 m long)

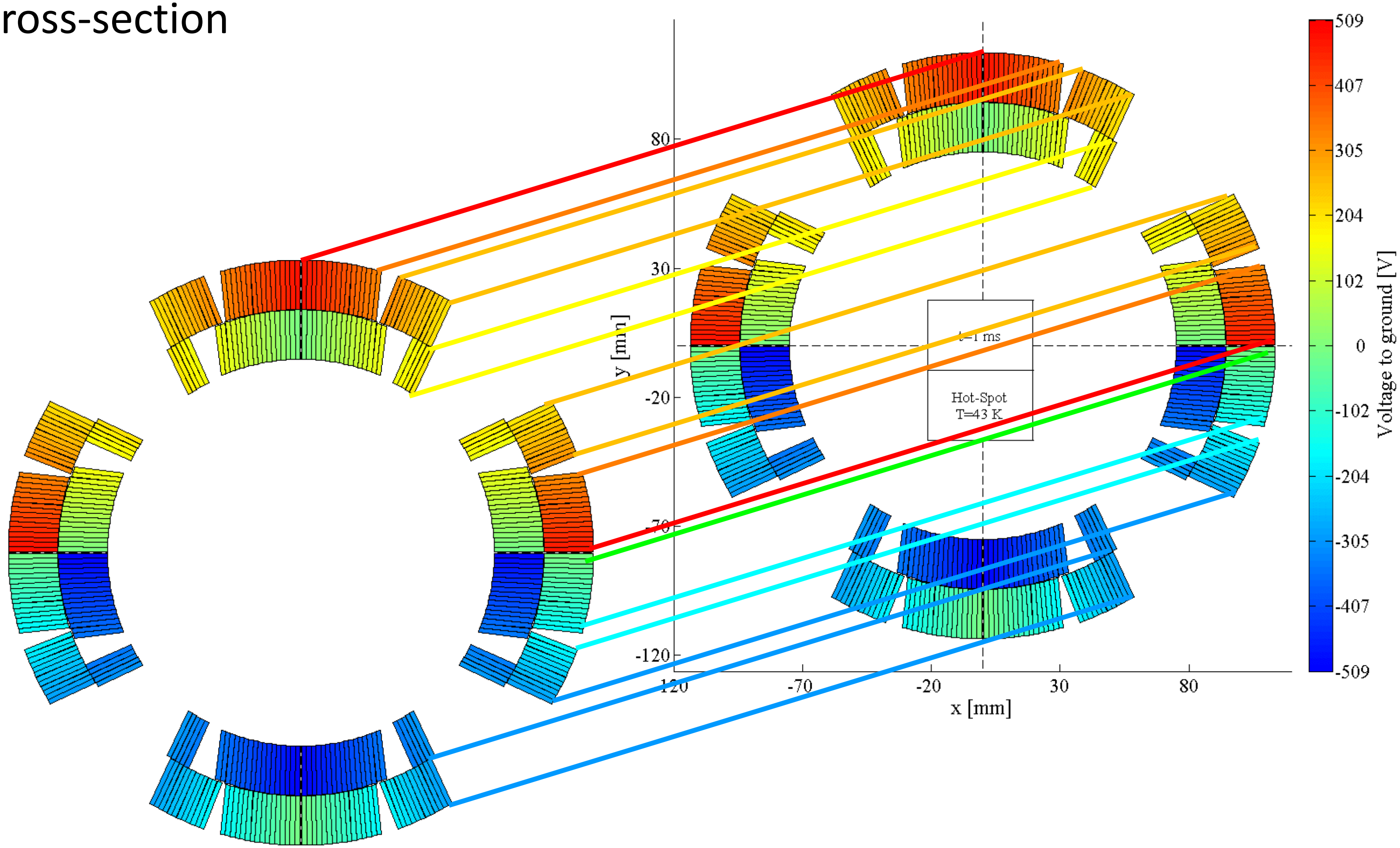


Cold mass test (2x 4.2 m long)



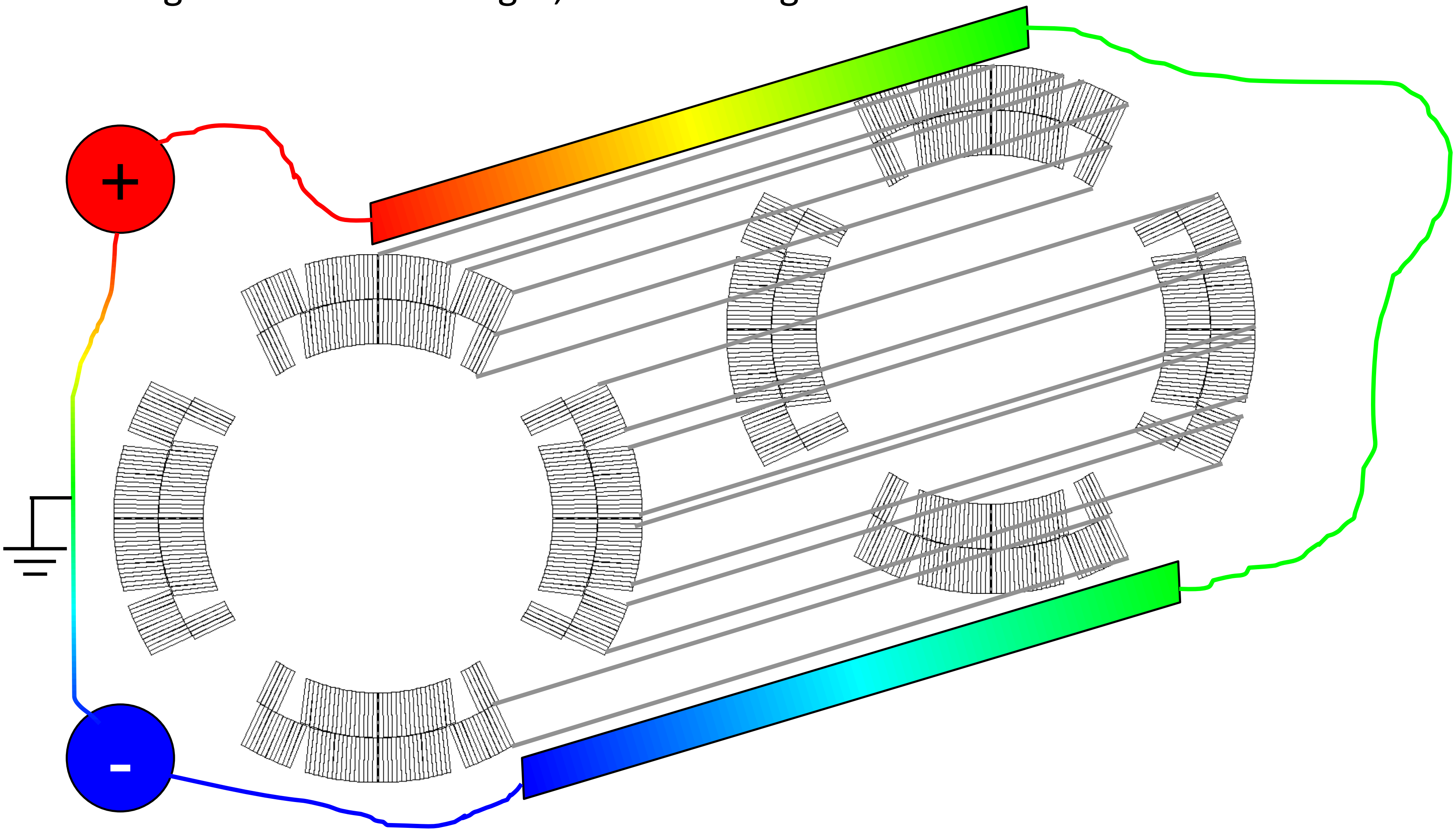
CLIQ-induced voltage distribution

- The voltage distribution in the windings just after triggering CLIQ remains almost constant along the magnet length, but is inhomogeneous in the magnet cross-section



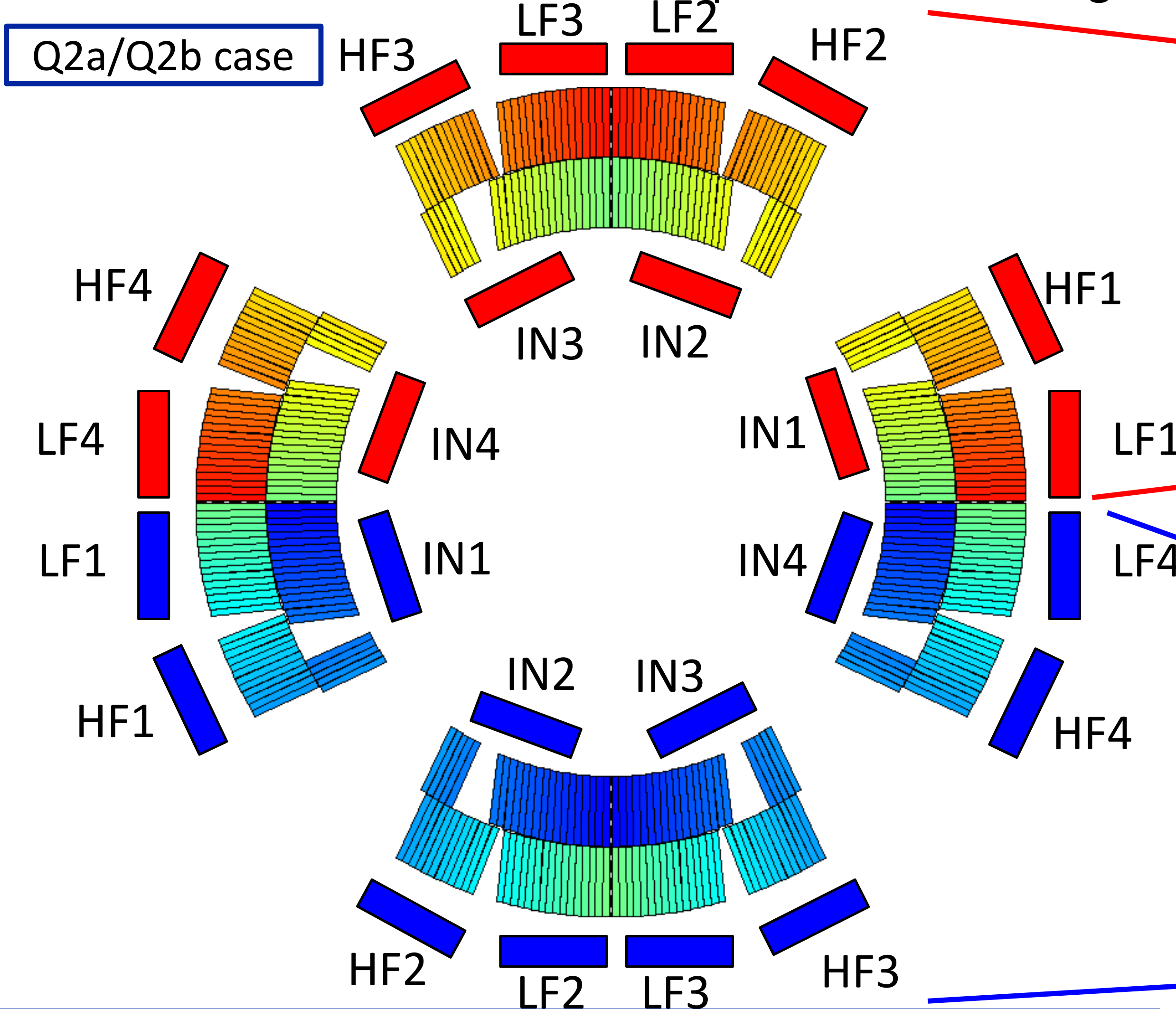
QH-induced voltage distribution

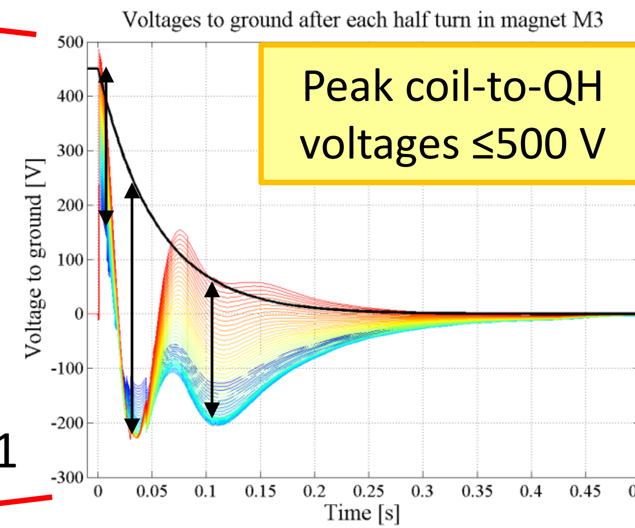
- The voltage distribution in the QH strips just after triggering varies linearly along the conductor length, but is homogeneous in the cross-section

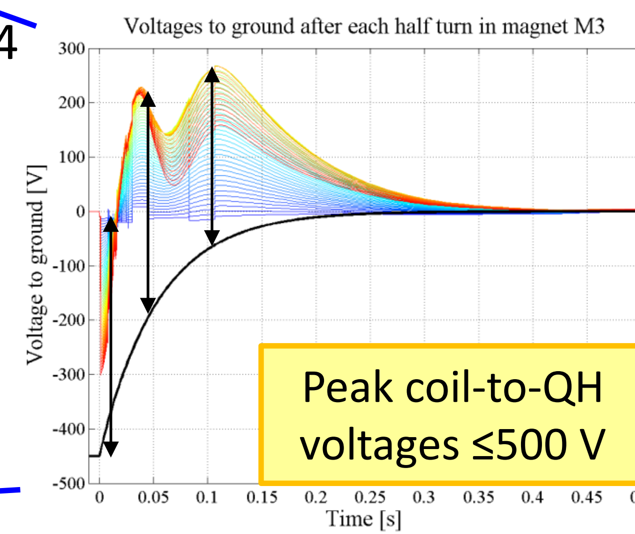


Coil to heater voltage optimization

- CLIQ and QH are triggered simultaneously. It is important to choose a QH connection scheme that compensates the voltages induced by CLIQ and QH







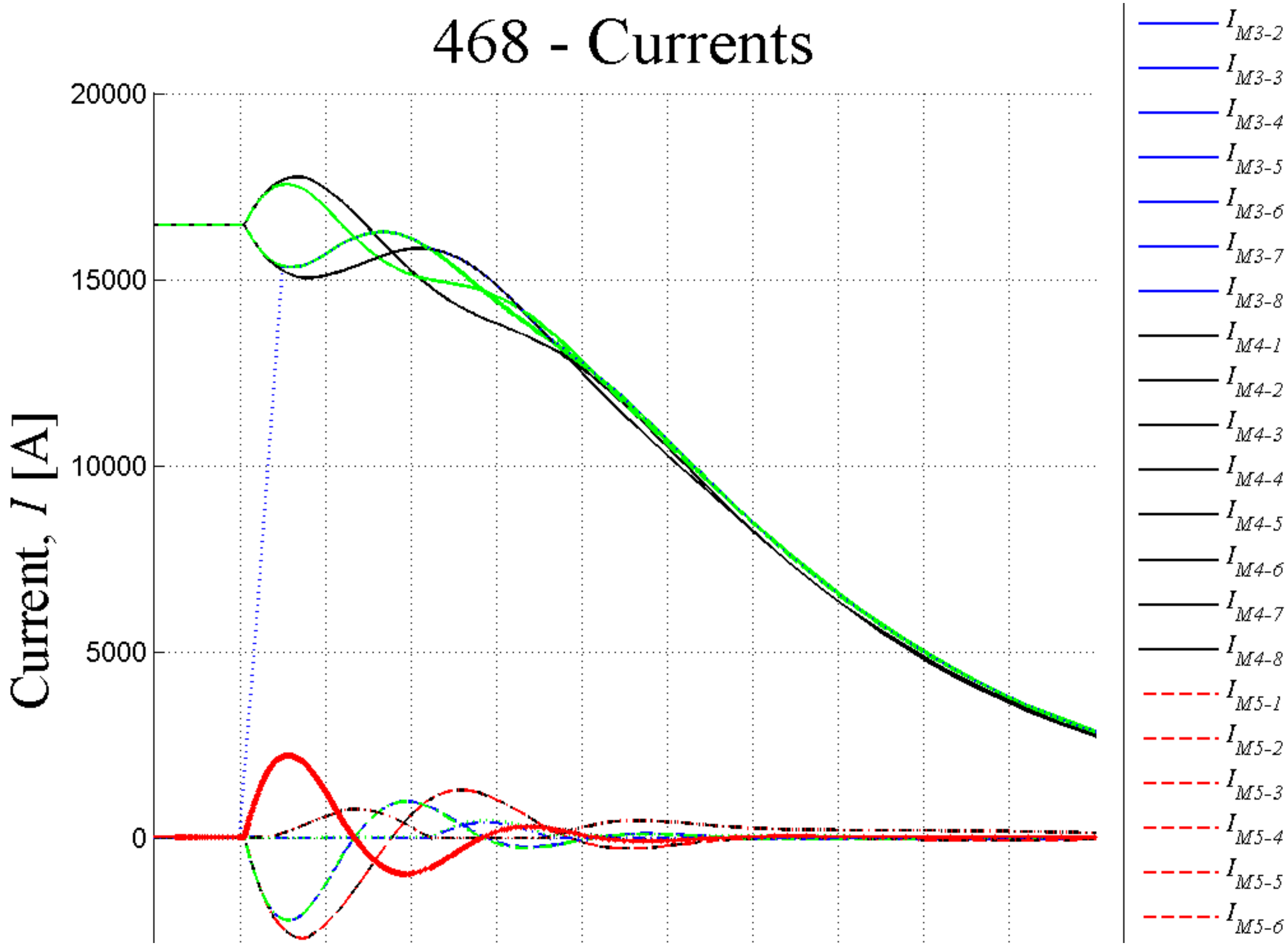
Summary of failure cases -1

Failure	Consequences	Probability	Mitigation
One QH supply (2 strips) not triggered	Hot-spot T = Peak voltage to ground =	Low	Parallel diodes CLIQ
Two QH supplies (4 strips) not triggered	Hot-spot T = Peak voltage to ground =	Very low	Parallel diodes CLIQ
CLIQ capacitor in open circuit	Hot-spot T = Peak voltage to ground = ~500 A through the diodes	Low	Capacitors in parallel Parallel diodes
CLIQ capacitor in short circuit	Hot-spot T = Peak voltage to ground = ~1 kA through the diodes	Very low	Capacitors in series Parallel diodes
One CLIQ unit triggered spuriously	Hot-spot T = Peak voltage to ground = ~2 kA through the diodes	Very low	Units interlocked Parallel diodes
One CLIQ unit not triggered	Hot-spot T +70 K (290-305 K) Peak voltage to ground = ~2.5 kA through the diodes	Very low	Double triggers Voltage monitor Parallel diodes QH
One CLIQ unit <u>and</u> one QH supply not triggered	Hot-spot T +70 K (290-305 K) Peak voltage to ground = ~2.5 kA through the diodes	Very low	QH connection scheme Parallel diodes

Summary of failure cases -2

Failure	Consequences	Probability	Mitigation
One parallel element disconnected	Hot-spot T = Peak voltage to ground = ~500 A through the diodes	Very low	
One lead of the parallel elements disconnected	Hot-spot T = Peak voltage to ground = ~500 A through the diodes	Very low	
Two leads of the parallel elements disconnected	Hot-spot T = Peak voltage to ground 600 V ~500 A through the diodes	Nihil	Monitoring currents in the circuit during each discharge
Entire CLIQ unit in short circuit	Hot-spot T +70 K (<300 K) Peak voltage to ground = ~2.5 kA through the diodes CLIQ unit to replace	Nihil	Capacitors in series CLIQ chargers protected QH
One CLIQ unit not triggered <u>and</u> one lead of the parallel elements disconnected	Hot-spot T +50 K (<280 K) Peak voltage to ground 1.6 kV ~1.5 kA through the diodes	Nihil	Monitoring currents in the circuit during each discharge
One CLIQ unit <u>and</u> all QH protecting the same magnet not triggered	Hot-spot T >500 K Magnet current through the diodes	Nihil	Redundant triggers for CLIQ and QH

Sim- 1 QH supply (2 strips) not triggered

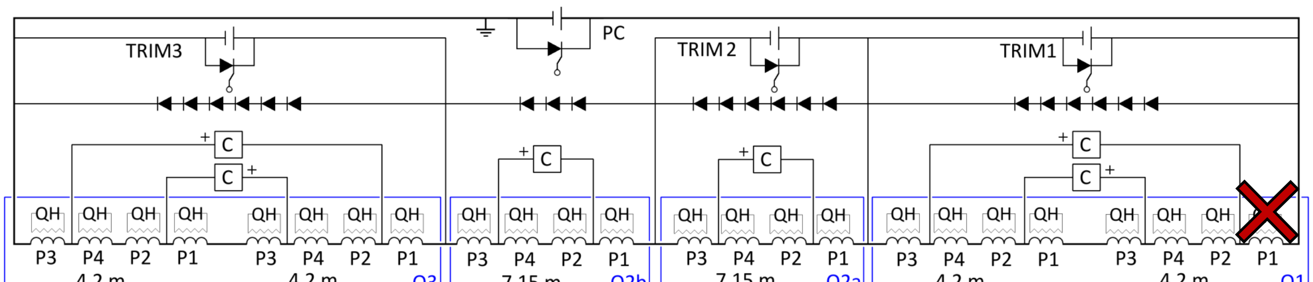


D
4-CLIQ 40 mF, 600 V
2-CLIQ 40 mF, 1 kV

Peak voltages to ground unchanged
300 500 V
(Q1/Q3 Q2a/Q2b)

Hot-spot temperature unchanged

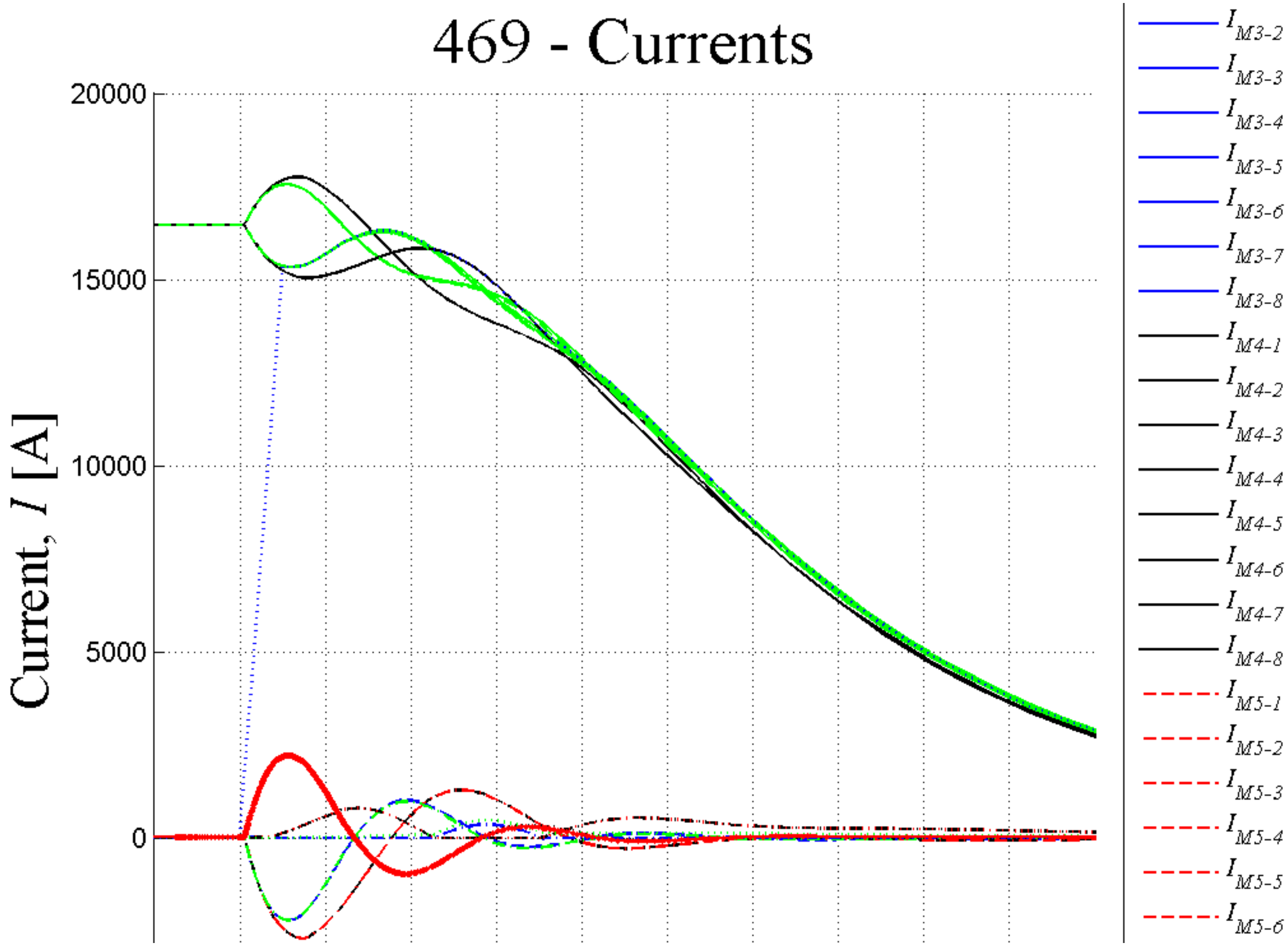
Peak current in the parallel elements
500-750 A
for 50-100 ms



Sim- 2 QH supplies (4 strips) not trig'd

LARP

High Luminosity LHC

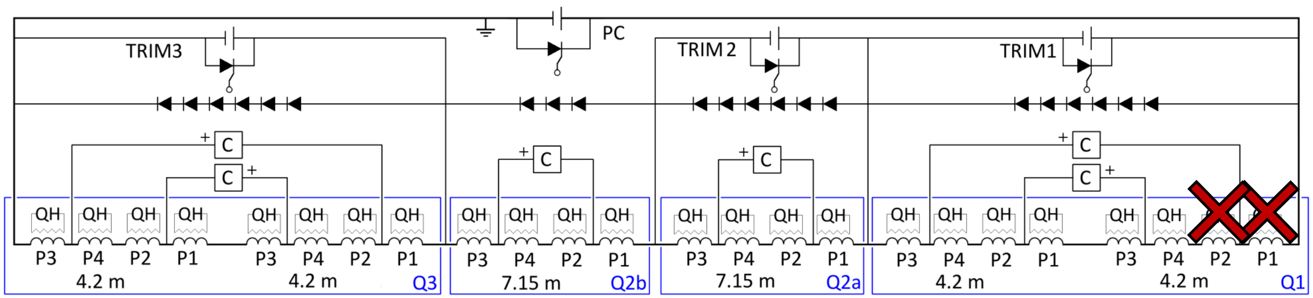


D
4-CLIQ 40 mF, 600 V
2-CLIQ 40 mF, 1 kV

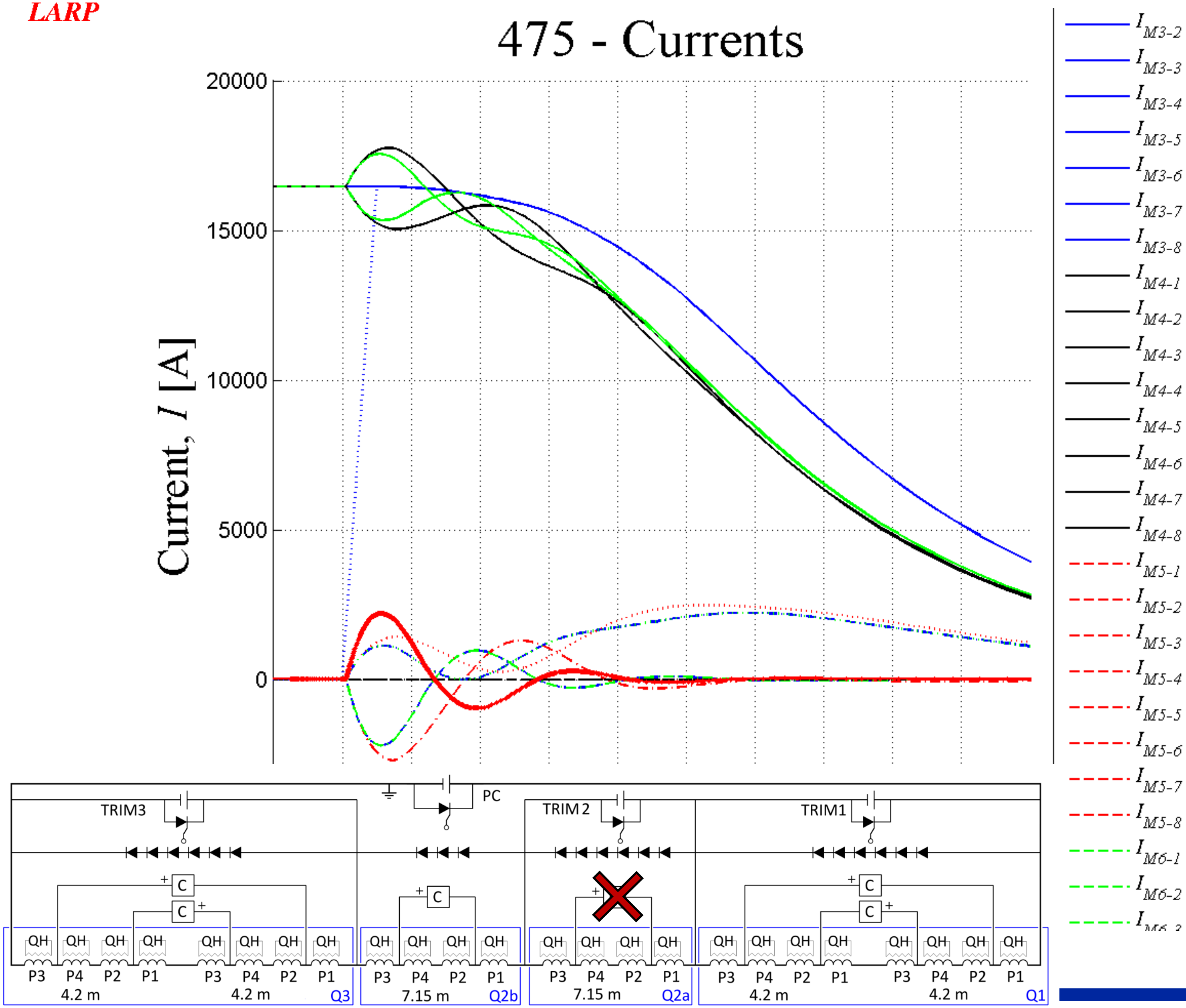
Peak voltages to ground unchanged
300   500 V
(Q1/Q3 Q2a/Q2b)

Hot-spot temperature unchanged

Peak current in the parallel elements
500-750 A
for 50-100 ms



Sim- One CLIQ unit not triggered



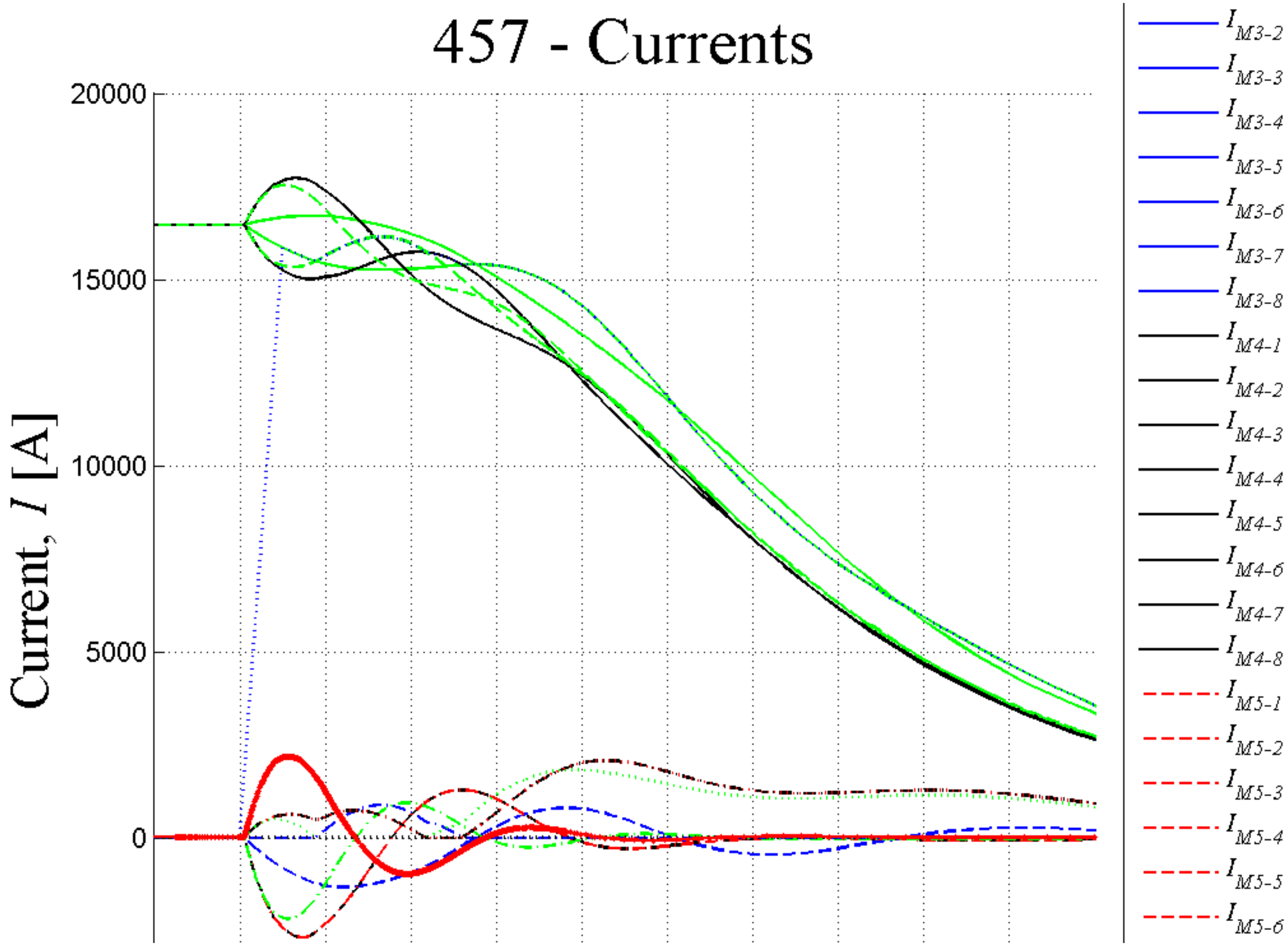
D
4-CLIQ 40 mF, 600 V
2-CLIQ 40 mF, 1 kV

Peak voltages to ground unchanged
300 500 V
(Q1/Q3 Q2a/Q2b)

Hot-spot temperature
305 K

Peak current in the parallel elements
2-2.5 kA
for 100-200 ms

Sim- One CLIQ unit not triggered

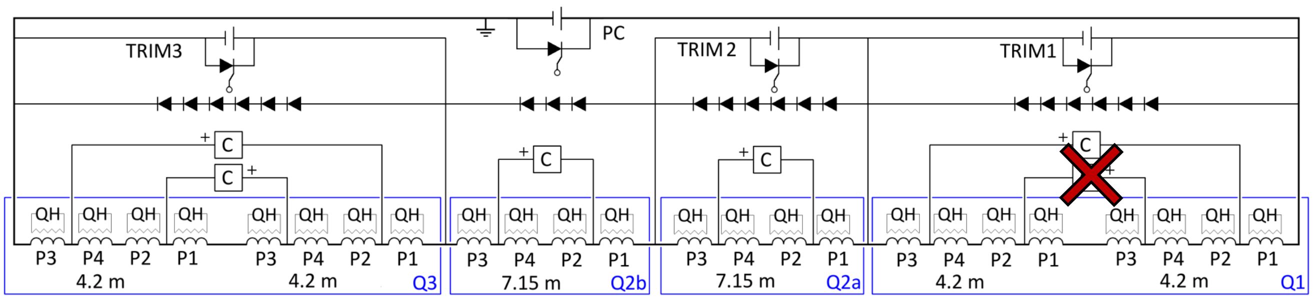


D
4-CLIQ 40 mF, 600 V
2-CLIQ 40 mF, 1 kV

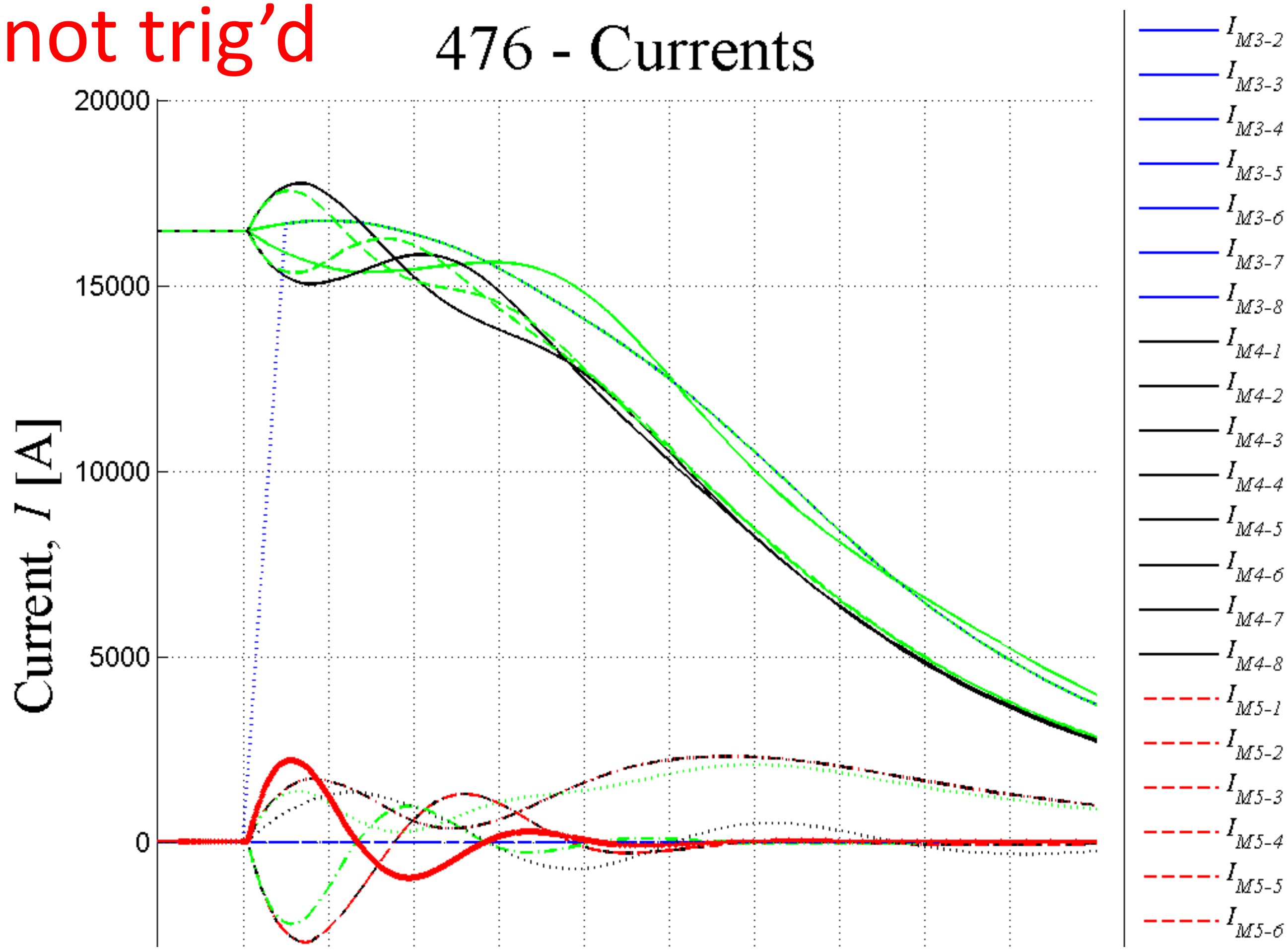
Peak voltages to ground unchanged
300 500 V
(Q1/Q3 Q2a/Q2b)

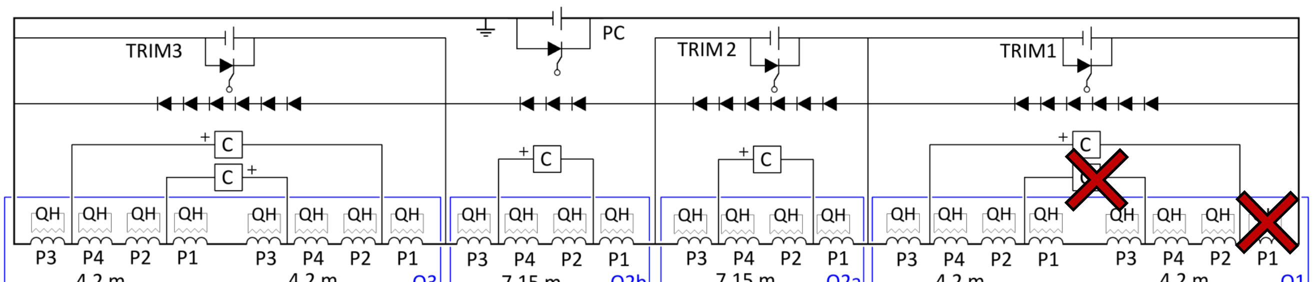
Hot-spot temperature
291 K

Peak current in the parallel elements
1.5-2 kA
for 100-200 ms



Sim- 1 CLIQ and 1 QH supply (2 strips) not trig'd





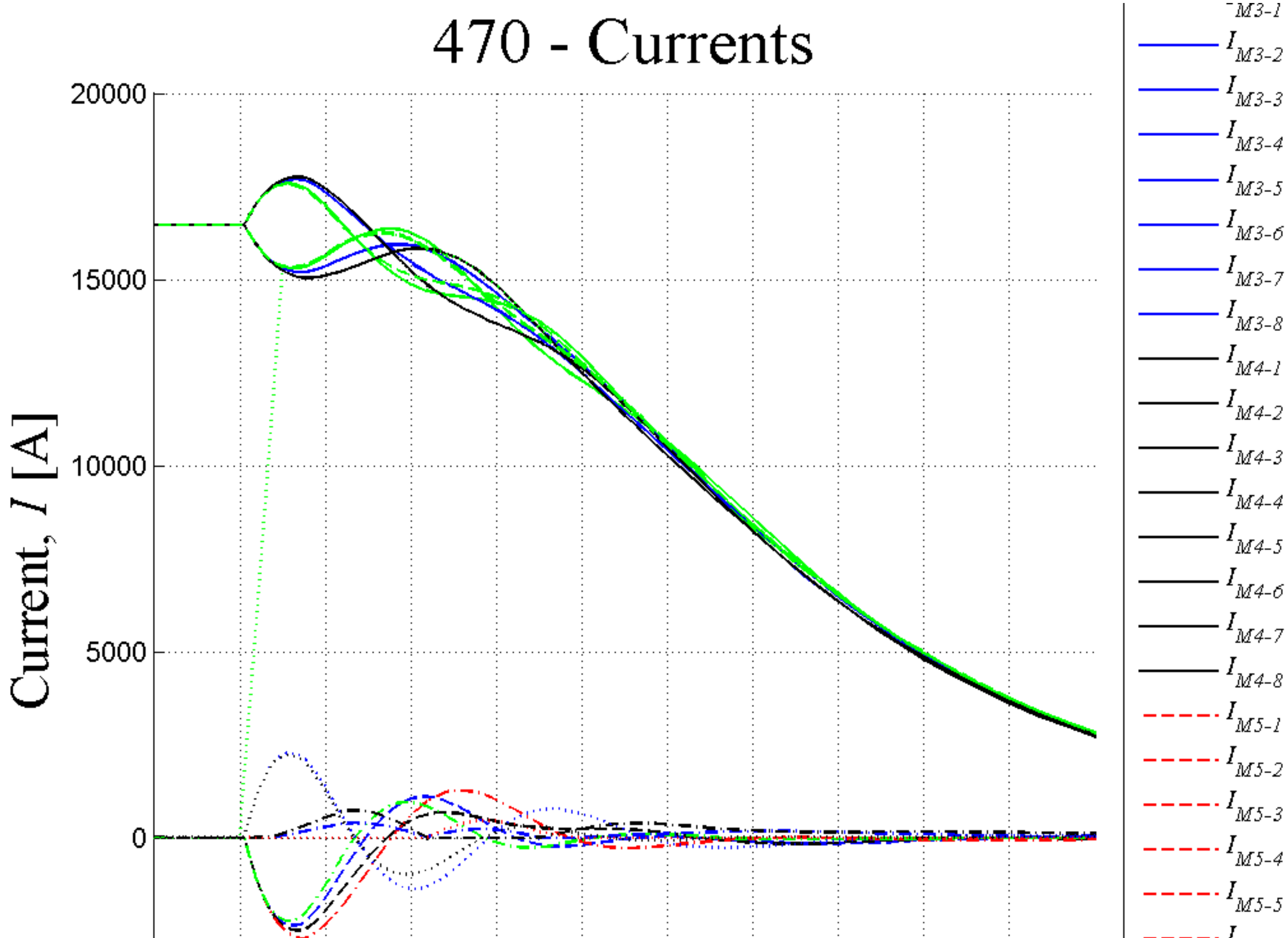
D
4-CLIQ 40 mF, 600 V
2-CLIQ 40 mF, 1 kV

Peak voltages to ground unchanged
300 500 V
(Q1/Q3 Q2a/Q2b)

Hot-spot temperature
299 K

Peak current in the parallel elements
2-2.5 kA
for 100-300 ms

Sim- Disconnection of one parallel lead

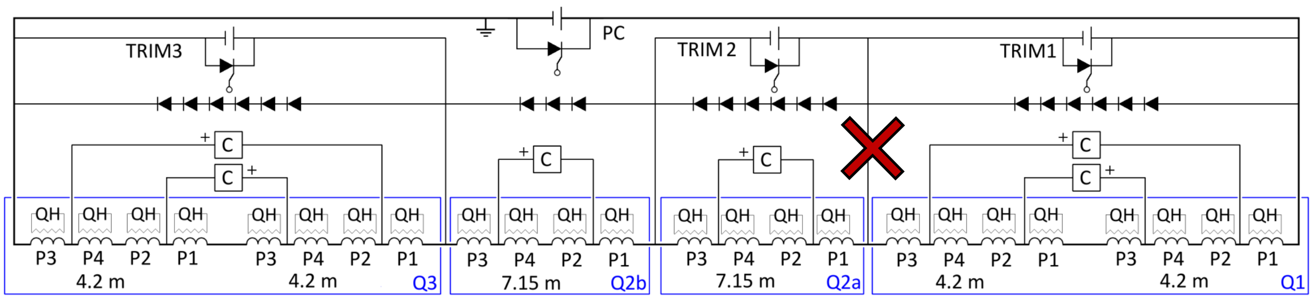


D
4-CLIQ 40 mF, 600 V
2-CLIQ 40 mF, 1 kV

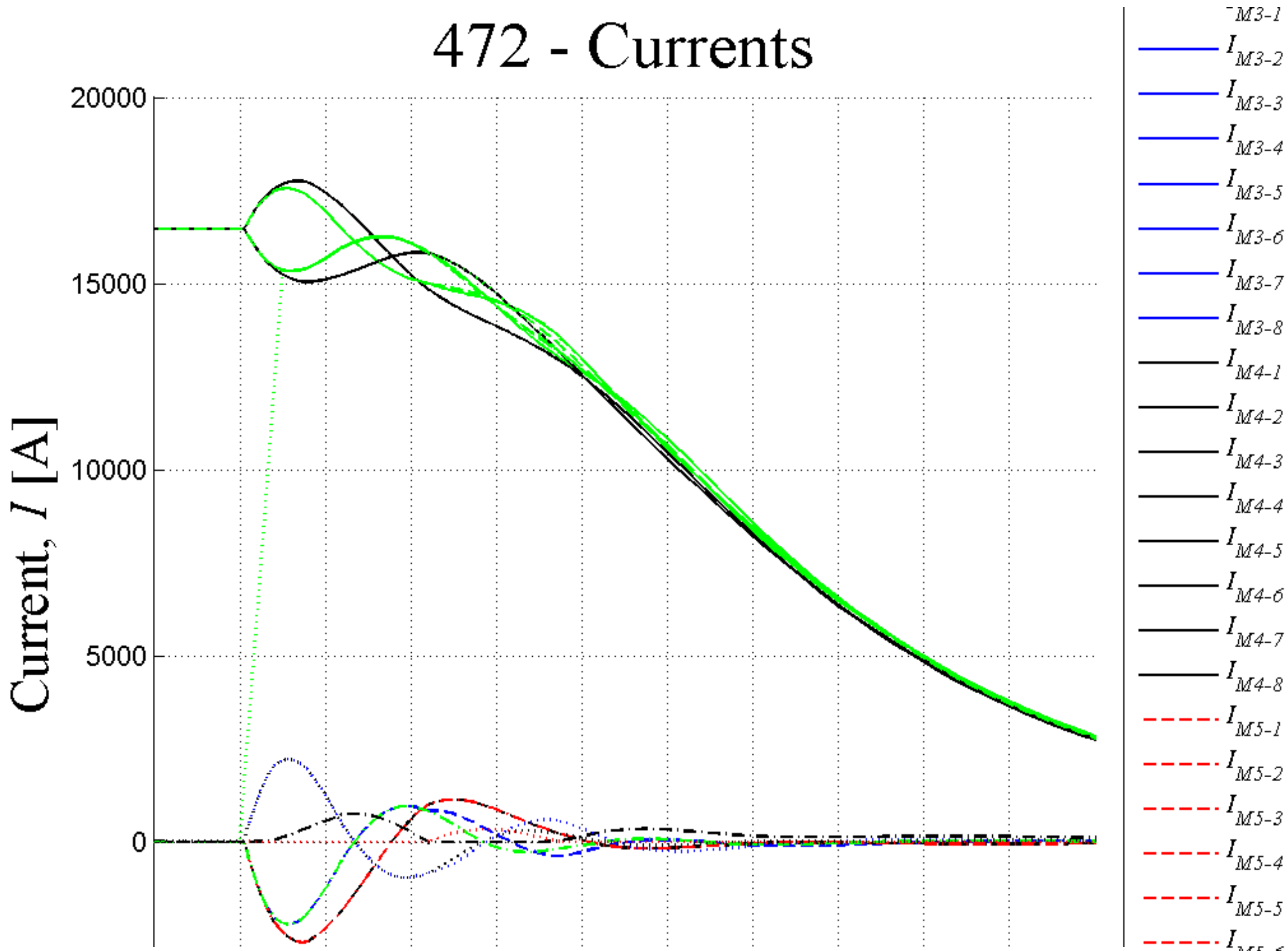
Peak voltages to ground slightly increased
375 500 V
(Q1/Q3 Q2a/Q2b)

Hot-spot temperature unchanged

Peak current in the parallel elements
500-750 A
for 50-100 ms



Sim- Disconnection of a parallel diode

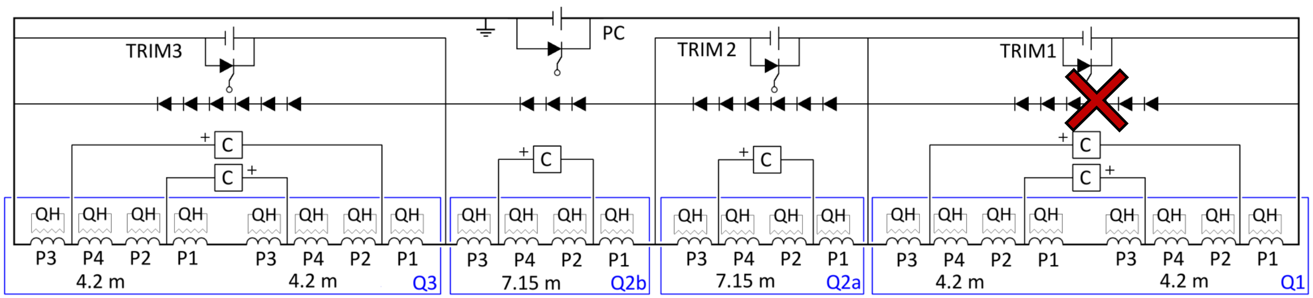


D
4-CLIQ 40 mF, 600 V
2-CLIQ 40 mF, 1 kV

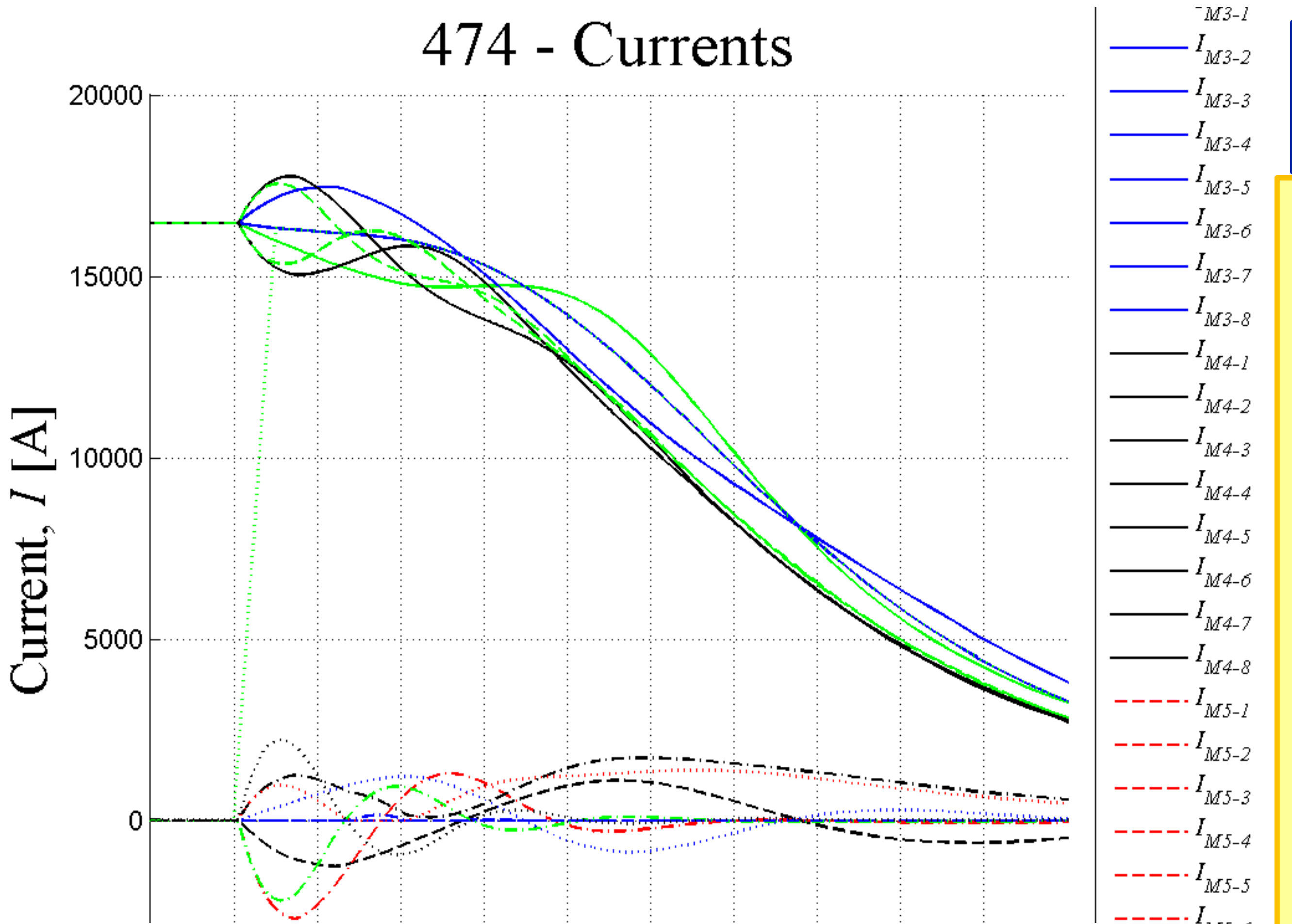
Peak voltages to ground slightly increased
385 500 V
(Q1/Q3 Q2a/Q2b)

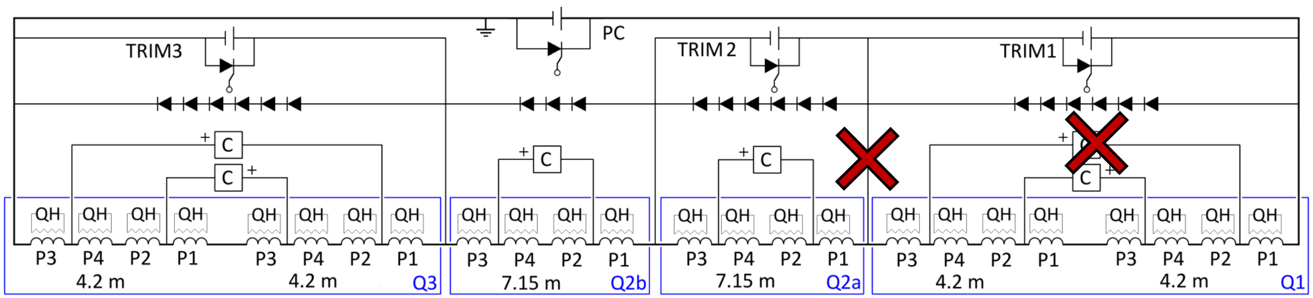
Hot-spot temperature unchanged

Peak current in the parallel elements
500 A
for <50 ms



Sim- CLIQ not trig'd + lead disconnected





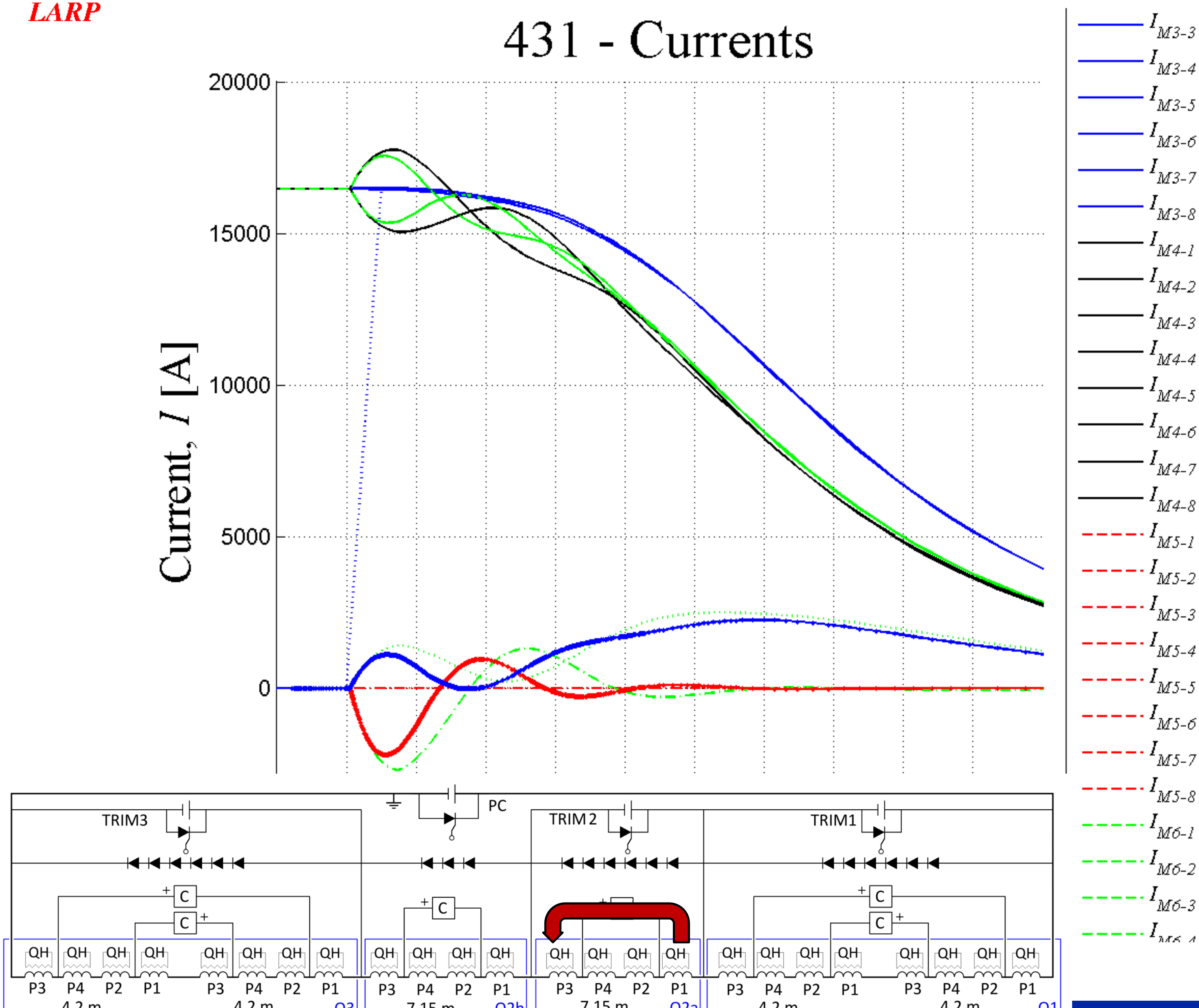
D
4-CLIQ 40 mF, 600 V
2-CLIQ 40 mF, 1 kV

Peak voltages to ground greatly increased!
1619 500 V
(Q1/Q3 Q2a/Q2b)

Hot-spot temperature 268-276 K in Q1 and Q2a

Peak current in the parallel elements 1-1.5 kA for 100-200 ms

Simulation of a short in a CLIQ unit



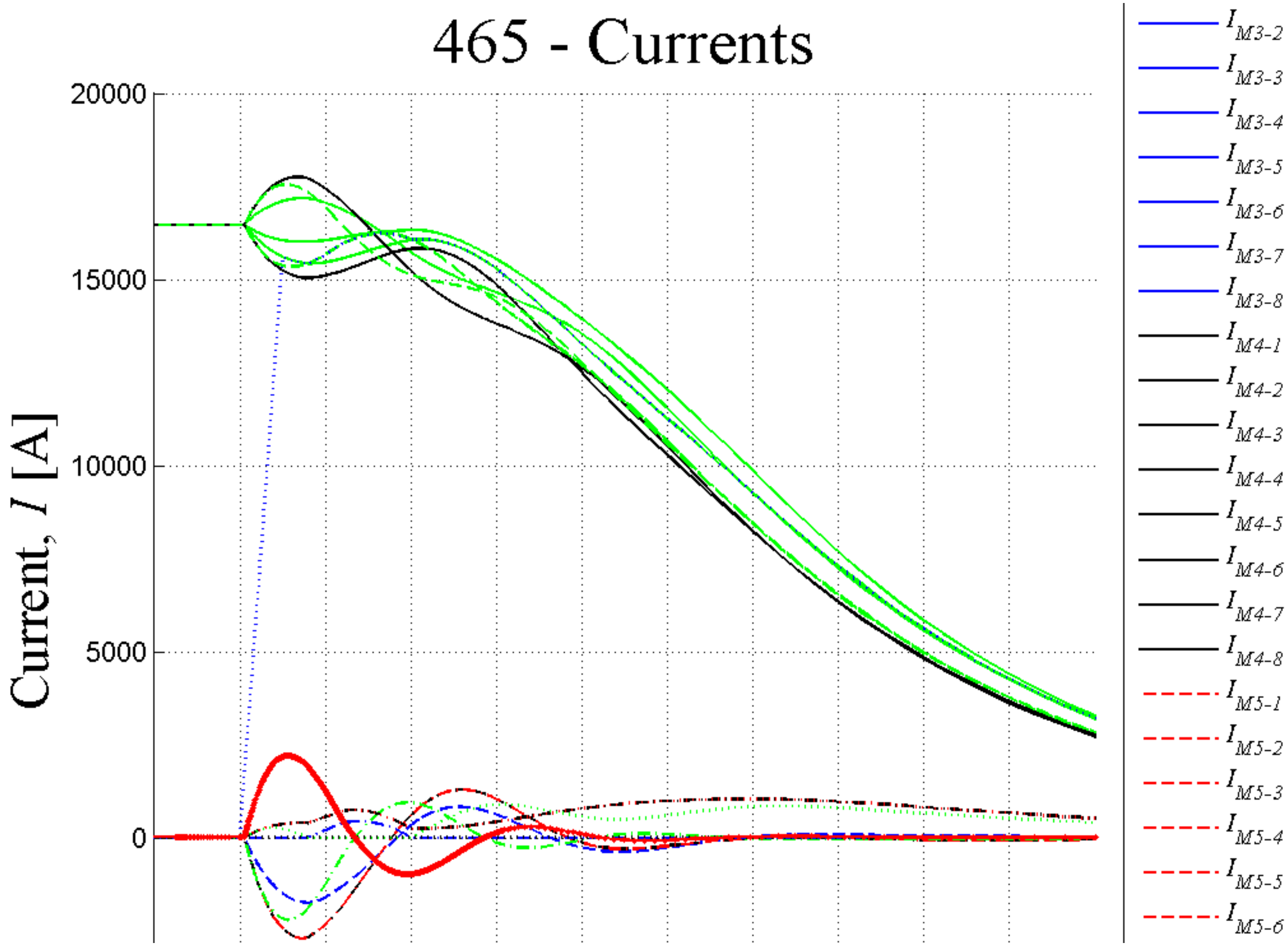
D
4-CLIQ 40 mF, 600 V
2-CLIQ 40 mF, 1 kV

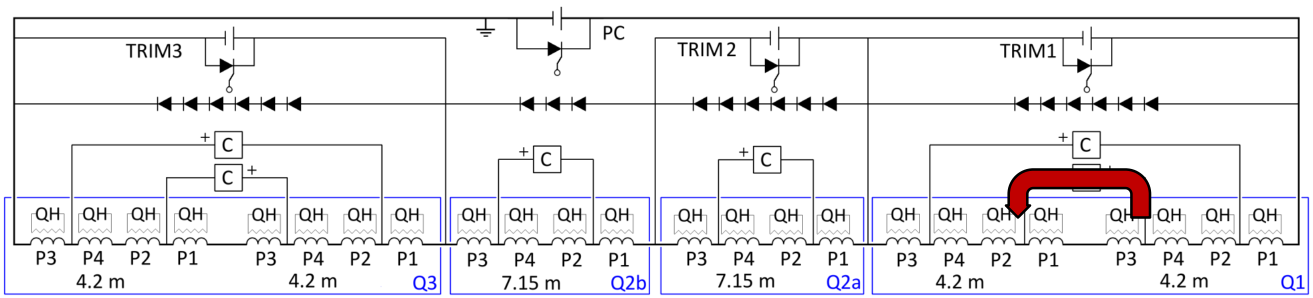
Peak voltages to ground unchanged
300 500 V
(Q1/Q3 Q2a/Q2b)

Hot-spot temperature
305 K

Peak current in the parallel elements
2-2.5 kA
for 100-200 ms

Simulation of a short in a CLIQ unit





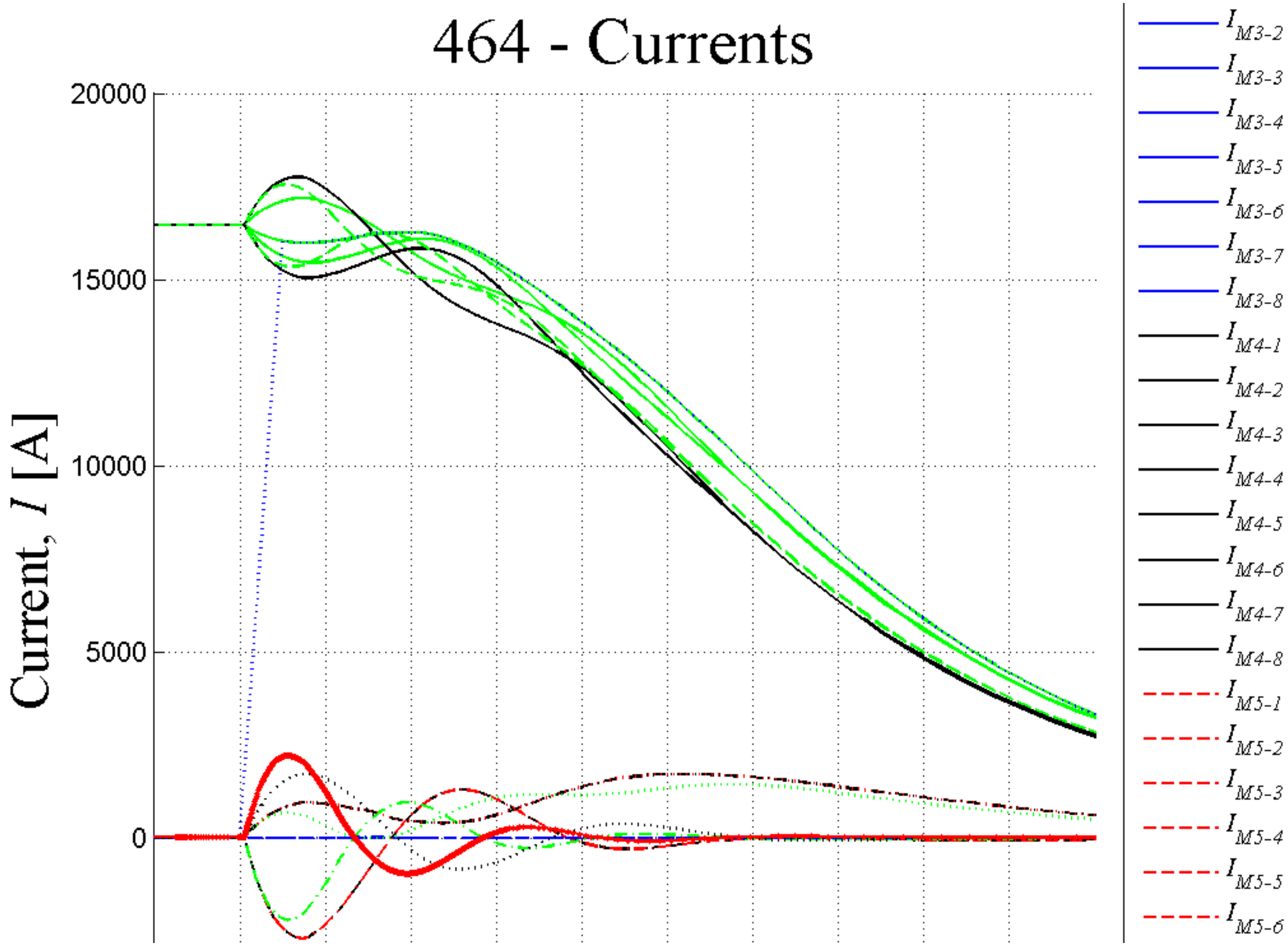
D
4-CLIQ 40 mF, 600 V
2-CLIQ 40 mF, 1 kV

Peak voltages to ground unchanged
300 500 V
(Q1/Q3 Q2a/Q2b)

Hot-spot temperature
300 K

Peak current in the parallel elements
0.5-1 kA
for 100-200 ms

Simulation of a short in a CLIQ unit

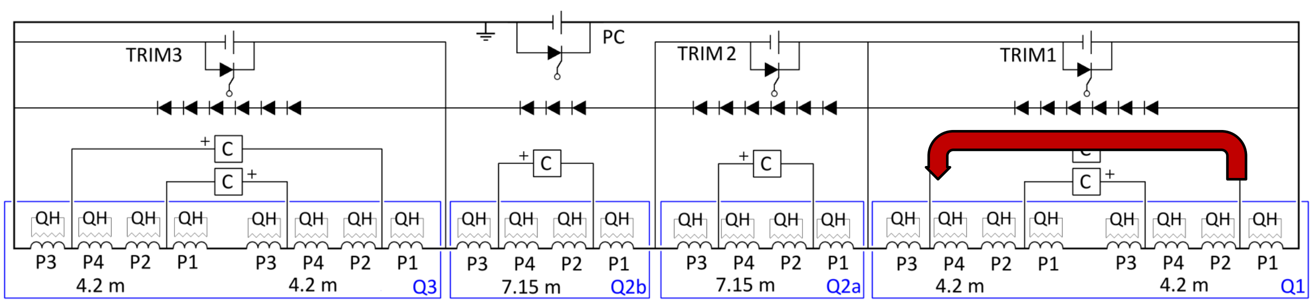


D
4-CLIQ 40 mF, 600 V
2-CLIQ 40 mF, 1 kV

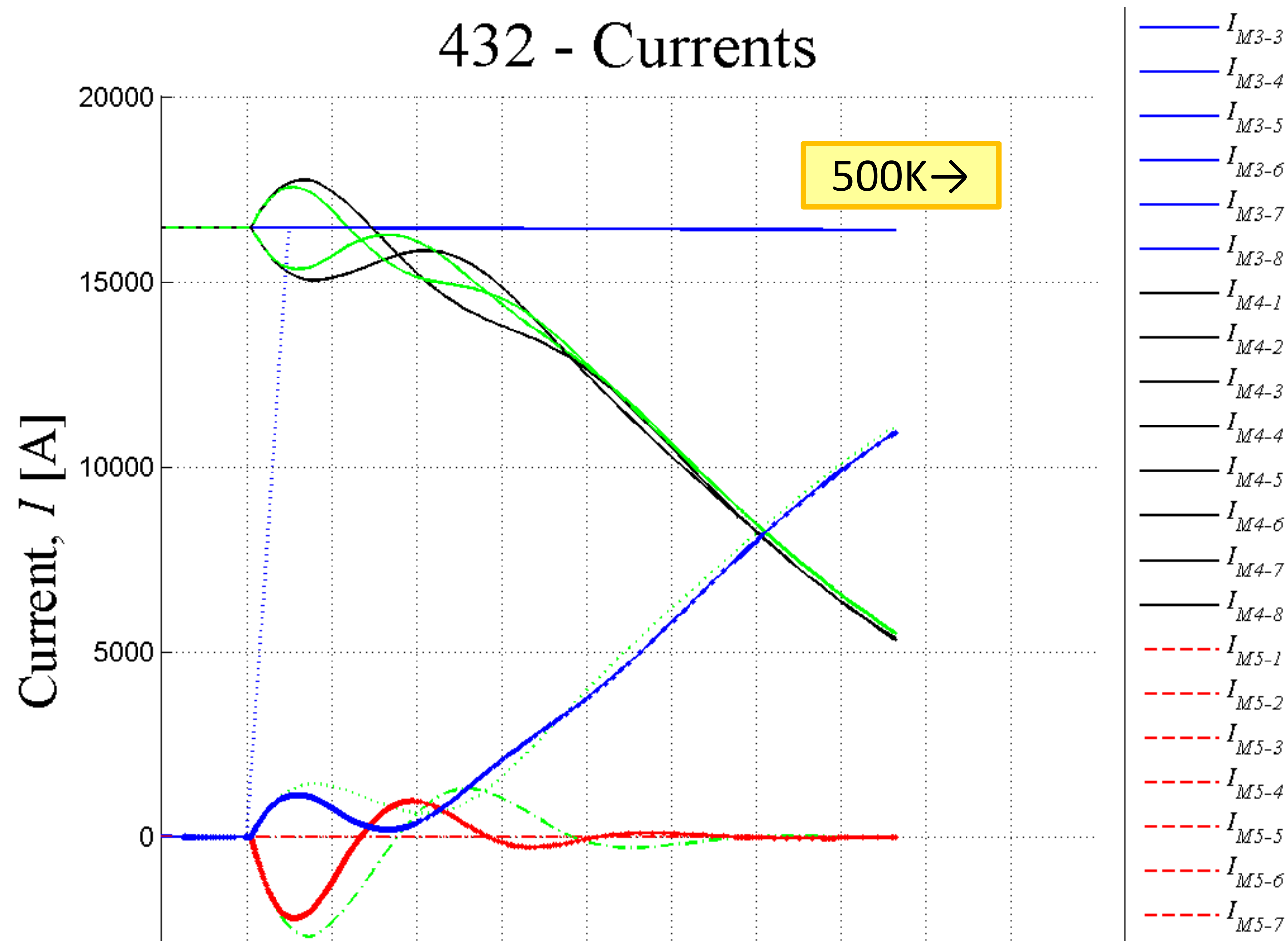
Peak voltages to ground unchanged
300 500 V
(Q1/Q3 Q2a/Q2b)

Hot-spot temperature
269 K

Peak current in the parallel elements
1-1.5 kA
for 100-200 ms



Sim- CLIQ and all QH not triggered

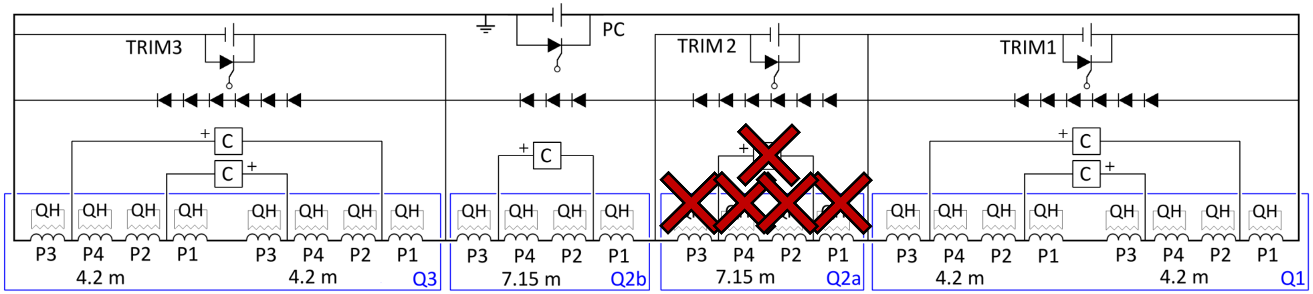


D
4-CLIQ 40 mF, 600 V
2-CLIQ 40 mF, 1 kV

Peak voltages to ground unchanged
300 500 V
(Q1/Q3 Q2a/Q2b)

Hot-spot temperature >>500 K

Parallel elements will receive the circuit current



Simulated characteristic voltages

Characteristic voltage	4-CLIQ 40mF/600V 2-CLIQ 40mF/1kV		4-CLIQ 40mF/1kV		4-CLIQ 40mF/600V Opt 2-CLIQ 40mF/1kV			
NO FAILURES	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b		
Peak voltage to ground [V]	**316**	513	513	509	**316**	512		
Turn to turn voltage [V]	16*	29*	16*	28*	19*	32*		
Mid-plane voltage [V]	**307**	509	500	512	**307**	509		
Layer to layer voltage [V]	295	496	**247**	492	296	495		
Layer-layer of adjacent poles [V]	600	1000	505	1000	600	1000		
CLIQ unit Q1 not triggered	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b		
Peak voltage to ground [V]	312	509	502	509	313	509		
Turn to turn voltage [V]	**28***	32*	**29***	32*	**28***	32*		
Mid-plane voltage [V]	307	512	497	512	307	512		
Layer to layer voltage [V]	295	492	246	492	297	492		
Layer-layer of adjacent poles [V]	600	1000	502	1000	600	1000		
CLIQ unit Q2a not triggered	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b		
Peak voltage to ground [V]	318	506	502	516	316	506		
Turn to turn voltage [V]	16*	**42***	19*	**47***	19*	**46***		
Mid-plane voltage [V]	307	512	497	512	307	512		
Layer to layer voltage [V]	295	492	246	492	492	492		
Layer-layer of adjacent poles [V]	600	1000	502	1000	600	1000		

Note: When not specified, peaks occur 1 ms after triggering the protection system. Values marked with "*" refer to a peak occurring 100-120 ms after triggering the protection system.

Simulated characteristic voltages

Characteristic voltage	4-CLIQ 40mF/600V 2-CLIQ 40mF/1kV		4-CLIQ 40mF/1kV		4-CLIQ 40mF/600V Opt 2-CLIQ 40mF/1kV			
Disconnection of 1 // lead	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b		
Peak voltage to ground [V]	**418***	522*			**375**	521		
Turn to turn voltage [V]	19*	32*			19*	33*		
Mid-plane voltage [V]	421	509			339	509		
Layer to layer voltage [V]	295	499			296	500		
Layer-layer of adjacent poles [V]	600	1000			600	1000		
Disconnection of 2 // leads	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b		
Peak voltage to ground [V]	**527***	**642***						
Turn to turn voltage [V]	19*	32*						
Mid-plane voltage [V]	493	509						
Layer to layer voltage [V]	295	498						
Layer-layer of adjacent poles [V]	600	1000						
One // diode in open circuit	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b		
Peak voltage to ground [V]					**385**	521		
Turn to turn voltage [V]					19*	32*		
Mid-plane voltage [V]					314	509		
Layer to layer voltage [V]					296	498		
Layer-layer of adjacent poles [V]					600	1000		

Note: When not specified, peaks occur 1 ms after triggering the protection system. Values marked with "*" refer to a peak occurring 100-120 ms after triggering the protection system.

Simulated characteristic voltages

Characteristic voltage	4-CLIQ 40mF/600V 2-CLIQ 40mF/1kV		4-CLIQ 40mF/1kV		4-CLIQ 40mF/600V Opt 2-CLIQ 40mF/1kV			
1 OutHF QH not triggered	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b		
Peak voltage to ground [V]	318	513			316	512		
Turn to turn voltage [V]	20*	32*			19*	32*		
Mid-plane voltage [V]	307	509			307	509		
Layer to layer voltage [V]	295	496			296	495		
Layer-layer of adjacent poles [V]	600	1000			600	1000		
2 OutHF QH not triggered	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b		
Peak voltage to ground [V]	316	513			318	512		
Turn to turn voltage [V]	21*	32*			20*	32*		
Mid-plane voltage [V]	307	509			307	509		
Layer to layer voltage [V]	295	496			296	495		
Layer-layer of adjacent poles [V]	600	1000			600	1000		
CLIQ unit Q1 not triggered and disconnection of 1 // lead	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b		
Peak voltage to ground [V]	**909**	509			**1619**	509		
Turn to turn voltage [V]	**33***	32*			32*	**50***		
Mid-plane voltage [V]	**801**	512			**707**	**1494**		
Layer to layer voltage [V]	295	492			295	492		
Layer-layer of adjacent poles [V]	725	1000			600	**1336**		

Note: When not specified, peaks occur 1 ms after triggering the protection system. Values marked with “*” refer to a peak occurring 100-120 ms after triggering the protection system.

Simulated characteristic voltages

Characteristic voltage	4-CLIQ 40mF/600V 2-CLIQ 40mF/1kV		4-CLIQ 40mF/1kV		4-CLIQ 40mF/600V Opt 2-CLIQ 40mF/1kV			
1CLIQ and 1 OutHF QH not trig'd	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b		
Peak voltage to ground [V]	324	509			**428**	509		
Turn to turn voltage [V]	**34***	32*			**29***	32*		
Mid-plane voltage [V]	307	512			**396**	512		
Layer to layer voltage [V]	295	492			339	296		
Layer-layer of adjacent poles [V]	600	1000			600	1000		
1CLIQ and 2 OutHF QH not trig'd	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b		
Peak voltage to ground [V]								
Turn to turn voltage [V]								
Mid-plane voltage [V]								
Layer to layer voltage [V]								
Layer-layer of adjacent poles [V]								
CLIQ Unit in short circuit	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b		
Peak voltage to ground [V]	318	506			302	509		
Turn to turn voltage [V]	19*	**46***			**29***	32*		
Mid-plane voltage [V]	307	512			307	512		
Layer to layer voltage [V]	295	492			296	492		
Layer-layer of adjacent poles [V]	600	1000			600	1000		

Note: When not specified, peaks occur 1 ms after triggering the protection system. Values marked with "*" refer to a peak occurring 100-120 ms after triggering the protection system.

No CLIQ – Sim characteristic voltages

Characteristic voltage	Q1/Q3	Q2a/Q2b
No CLIQ, With // diodes, 1 OutHF QH not trig'd	Q1/Q3	Q2a/Q2b
Peak voltage to ground [V]	**324***	**330***
Turn to turn voltage [V]	**34***	**46***
Mid-plane voltage [V]	**162***	**35***
Layer to layer voltage [V]	**240***	**374***
Layer-layer of adjacent poles [V]	**149***	**24***
No CLIQ, No // diodes, 1 OutHF QH not trig'd	Q1/Q3	Q2a/Q2b
Peak voltage to ground [V]	**616***	**729***
Turn to turn voltage [V]	**29***	**50***
Mid-plane voltage [V]	431*	**170***
Layer to layer voltage [V]	**245***	427*
Layer-layer of adjacent poles [V]	**223***	**111***
No CLIQ, No // diodes, 2 OutHF QH not trig'd	Q1/Q3	Q2a/Q2b
Peak voltage to ground [V]	**988***	**1020***
Turn to turn voltage [V]	**27***	**47***
Mid-plane voltage [V]	**802***	**229***
Layer to layer voltage [V]	408*	406*
Layer-layer of adjacent poles [V]	417*	**146***

Note: When not specified, peaks occur 1 ms after triggering the protection system. Values marked with "*" refer to a peak occurring 100-120 ms after triggering the protection system.

Simulated characteristic voltages

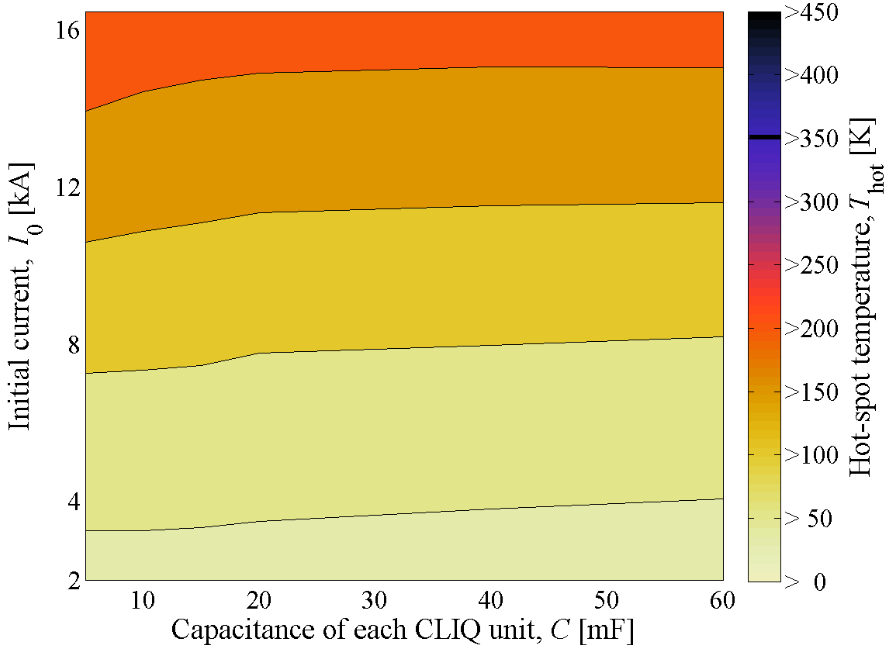
Characteristic voltage	4-CLIQ 40mF/600V 2-CLIQ 40mF/1kV		4-CLIQ 40mF/1kV		4-CLIQ 40mF/600V Opt 2-CLIQ 40mF/1kV			
***With CLIQ*, All QH not trig'd**	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b		
Peak voltage to ground [V]					**358**	**593**		
Turn to turn voltage [V]					**29***	**47***		
Mid-plane voltage [V]					307	509		
Layer to layer voltage [V]					296	495		
Layer-layer of adjacent poles [V]					600	1000		
***No CLIQ*, Only Out QH trig'd**	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b		
Peak voltage to ground [V]								
Turn to turn voltage [V]								
Mid-plane voltage [V]								
Layer to layer voltage [V]								
Layer-layer of adjacent poles [V]								
***No CLIQ*, Out and In QH trig'd**	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b	Q1/Q3	Q2a/Q2b		
Peak voltage to ground [V]					**179***	**285***		
Turn to turn voltage [V]					18*	30*		
Mid-plane voltage [V]					**46***	**34***		
Layer to layer voltage [V]					**115***	**193***		
Layer-layer of adjacent poles [V]					**47***	**34***		

Note: When not specified, peaks occur 1 ms after triggering the protection system. Values marked with "*" refer to a peak occurring 100-120 ms after triggering the protection system.

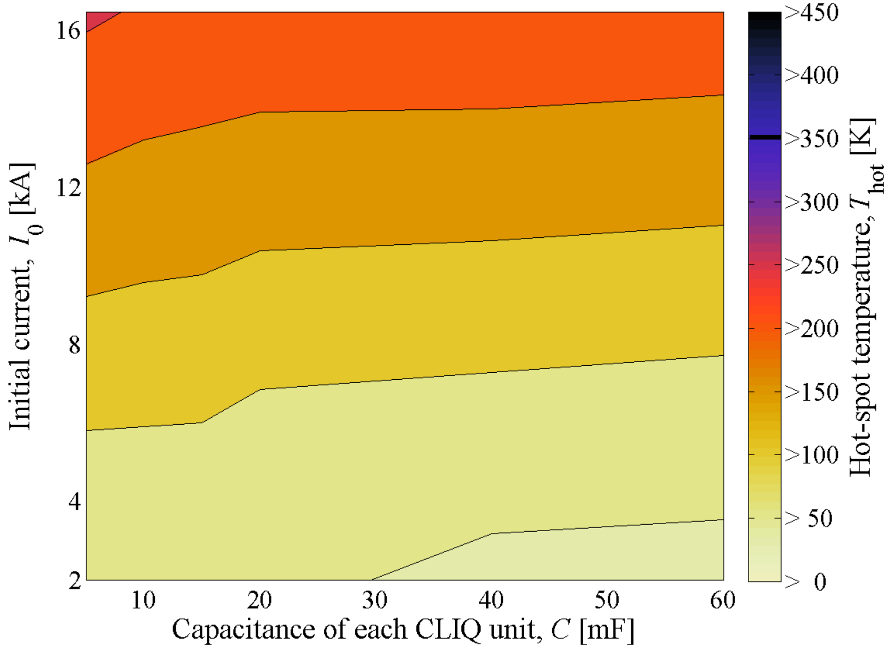
Level of redundancy

- Choose an optimum level of redundancy
  1. Reduce capacitance of CLIQ units to reduce their size and cost?
  2. Keep some QH as spares to reduce the risk of degradation?
  3. Redesign QH to be more effective at low-to-medium current? (Tiina)
- Next step: Once determined the baseline circuit, Failure cases with reduced number of QH units and with reduced capacitance of CLIQ units

Simulated hot-spot temperature



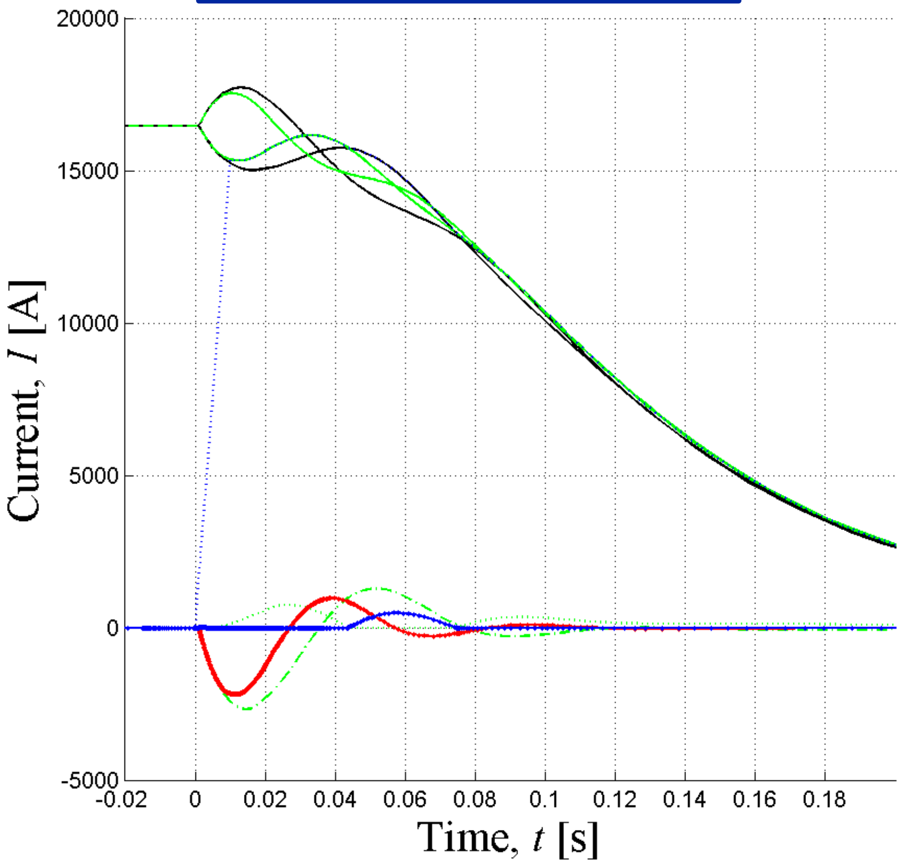
CLIQ + 4 HF QH strips + 4 LF QH strips



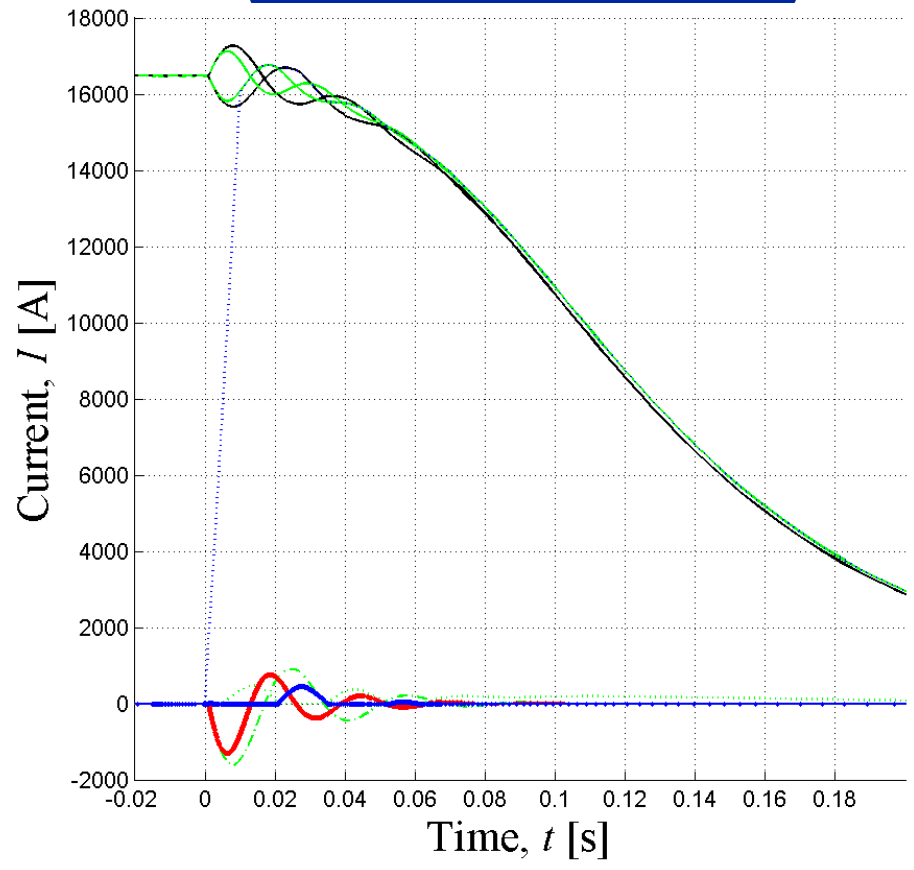
CLIQ + 4 HF QH strips

Simulated currents in the circuit

6-CLIQ, 40 mF



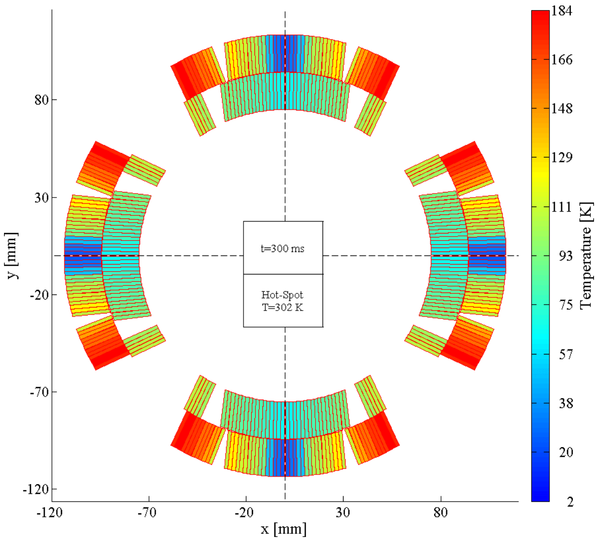
6-CLIQ, 10 mF



Simulated temperature profiles

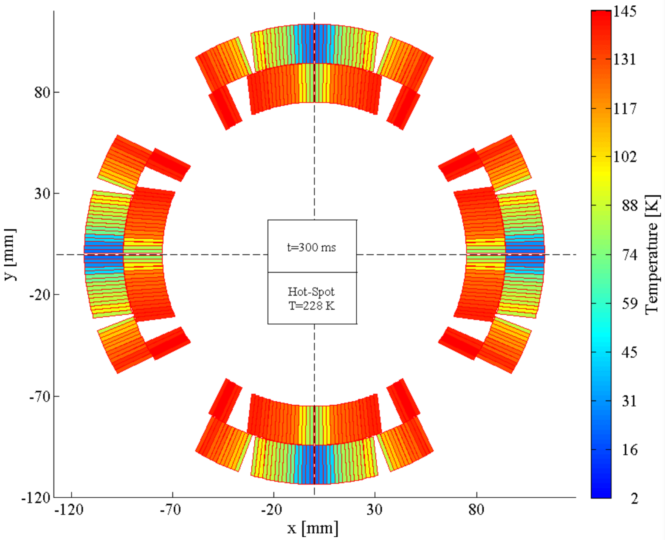
- CLIQ + Quench Heaters assure the most homogeneous temperature distribution in the coil windings at the end of a discharge
- Reducing the thermal gradients reduces the thermal stress

Outer QH



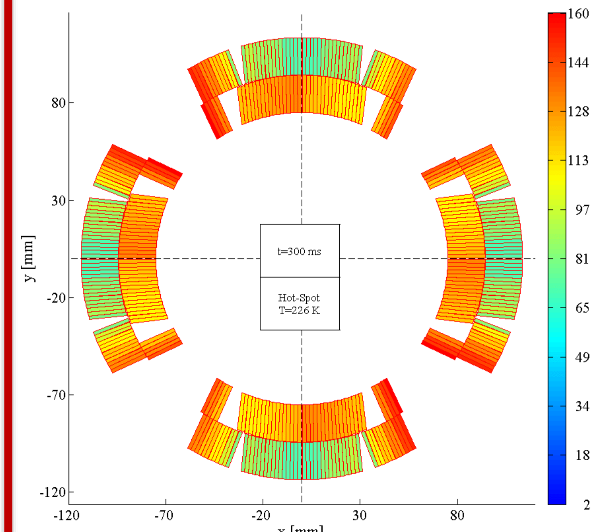
ΔT=140 K

Outer+Inner QH



ΔT=100 K

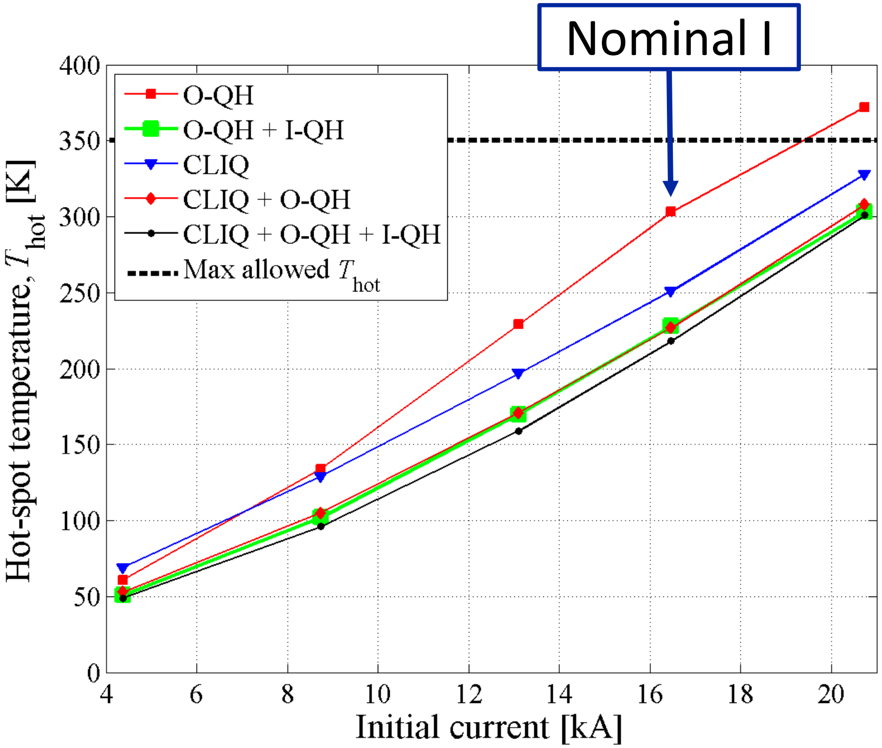
CLIQ + Outer QH



ΔT=85 K

Simulated hot-spot temperature

Protection system	Hot-spot T
CLIQ	250 K
CLIQ+8 outer QH's	230 K
CLIQ+8 outer QH's+4 inner QH's	220 K
CLIQ+4 outer QH in HF region	240 K



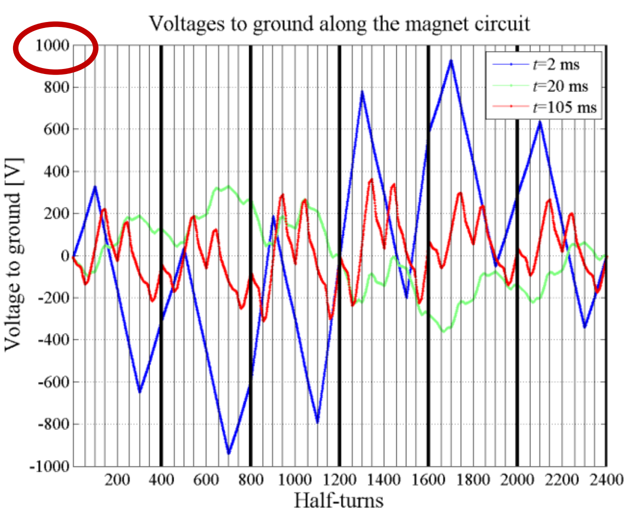
The more QH units are triggered, the higher the probability of degrading the electrical insulation

CLIQ+4 HF outer QH's seems the best compromise for reducing hot-spot temperature and thermal stress, and increasing redundancy and robustness.

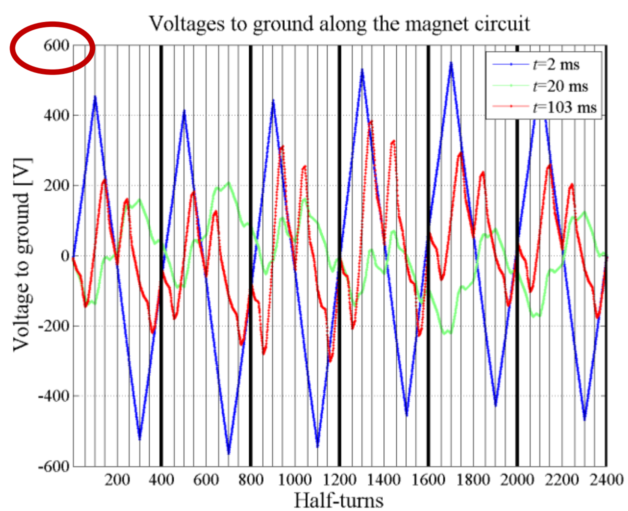
Why do we need parallel elements?

- Voltages to ground reduced by means of parallel elements across parts of the circuit which equalize the voltage distribution
- Avoid very high voltages to ground in several CLIQ failure cases
- Cold parallel diodes are probably incompatible with the very high expected radiation dose in the interaction regions
- Proposed solution: Warm parallel diodes utilizing existing leads of the trim supplies (but needs different connection schemes for Q1/Q3 and Q2a/Q2b)
- Back-up solution: 1Ω parallel resistors (but leakage currents, cryo loads)

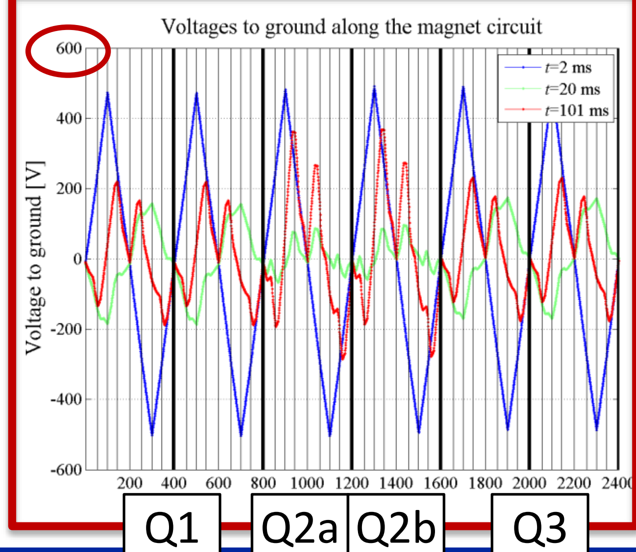
No parallel elements



1 Ω resistors

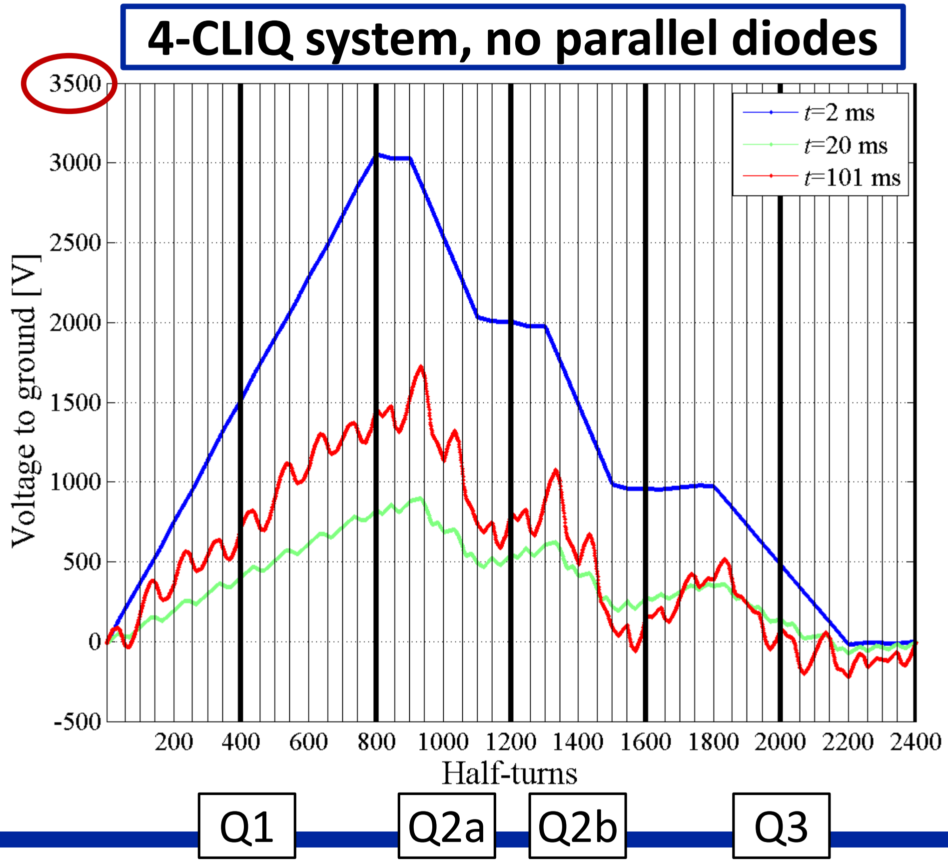


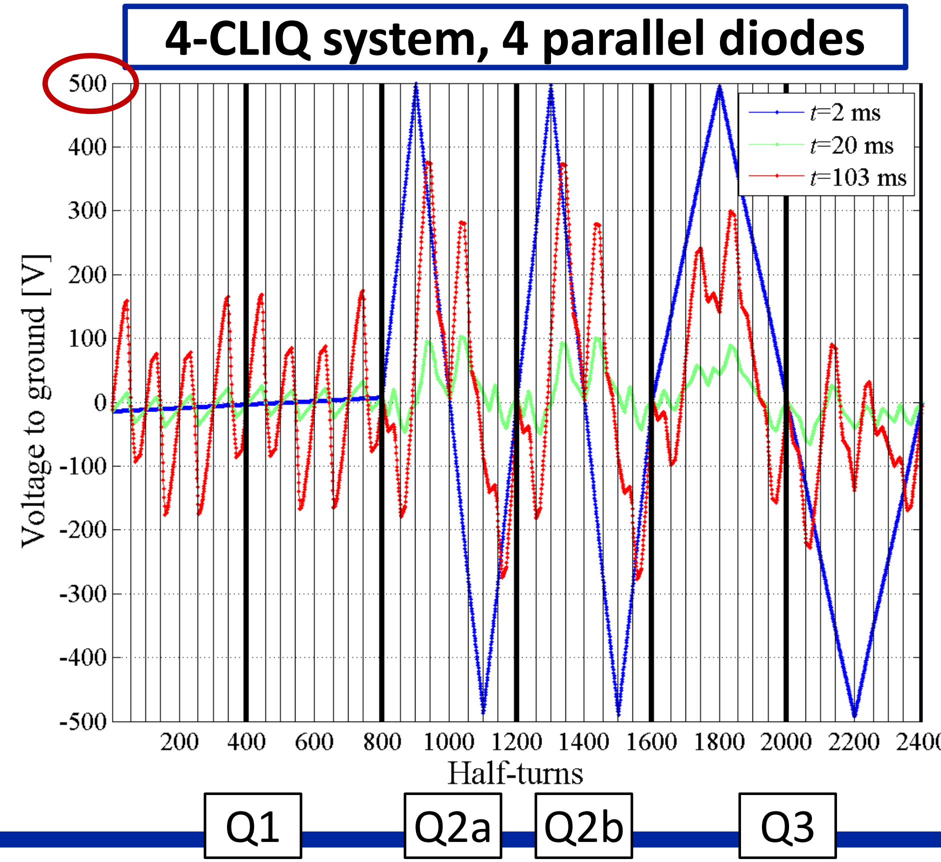
Warm diodes



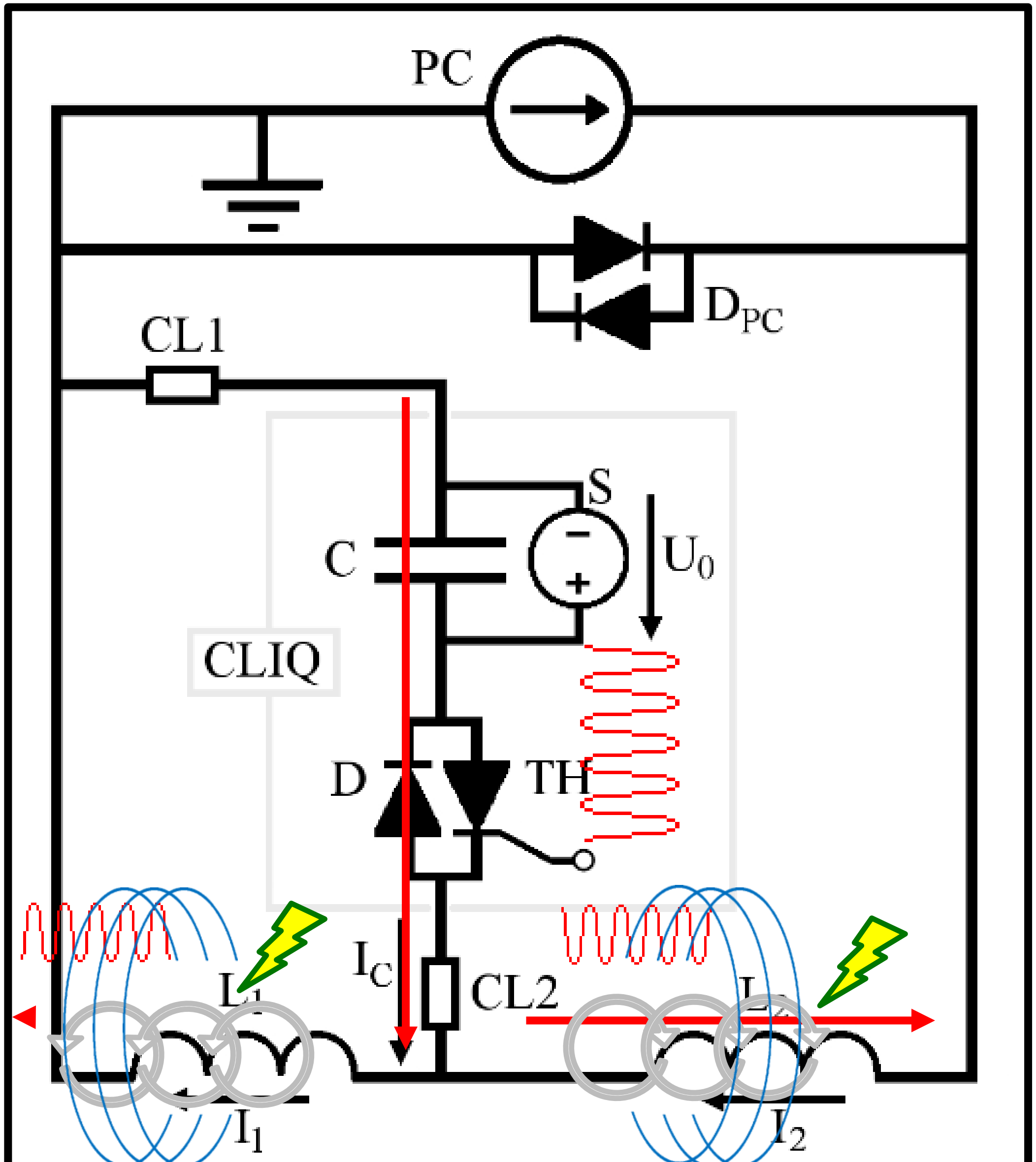
Why do we need parallel elements? Failure: One CLIQ unit not triggered

- Worst-case: CLIQ unit at one end of the circuit is not triggered
- Without parallel elements, the voltage to ground just after triggering the CLIQ units reach $3*U_0$=3 kV





What is CLIQ?



Current change

Magnetic field change

Coupling losses (Heat)

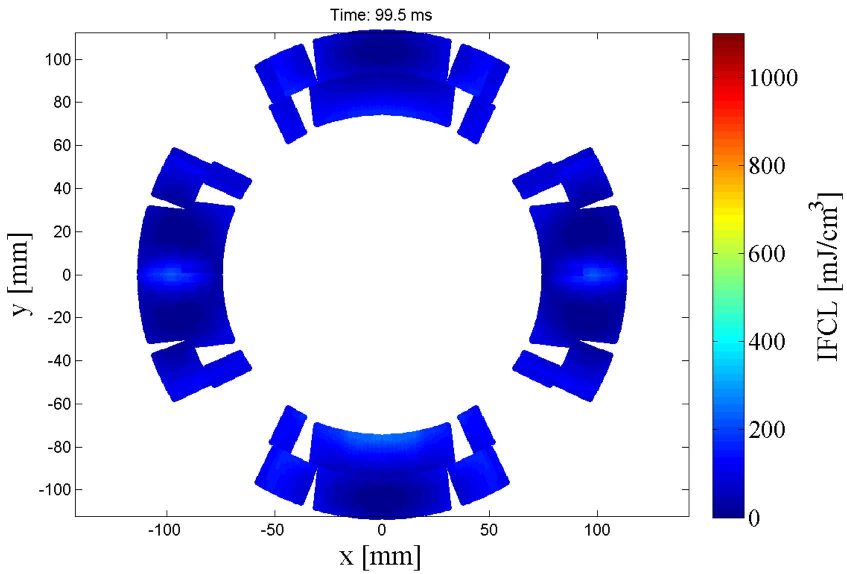
Temperature rise

QUENCH

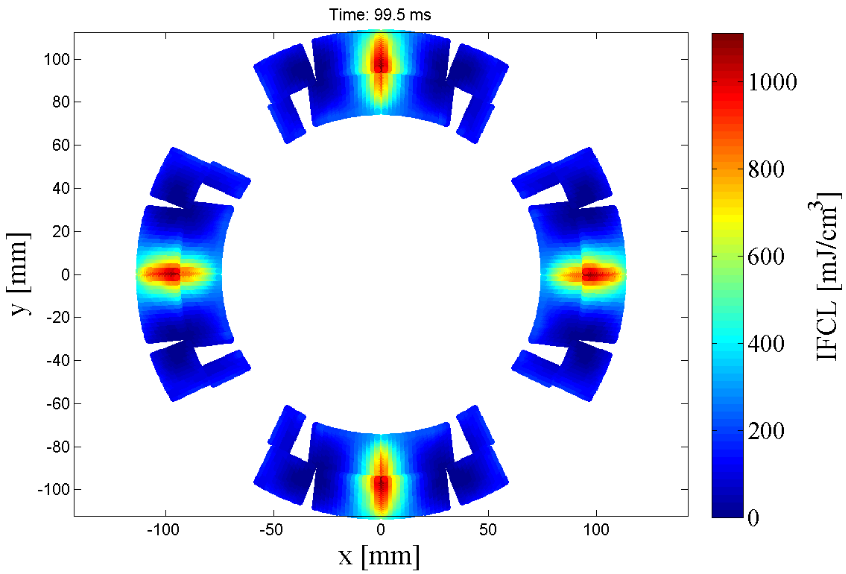
Why does it matter if the pole electrical order is different?

Depending on the connection of the CLIQ units to the magnets in the circuit, different coil sections will receive different current changes. For MQXF, two options are possible

Not optimized



Optimized



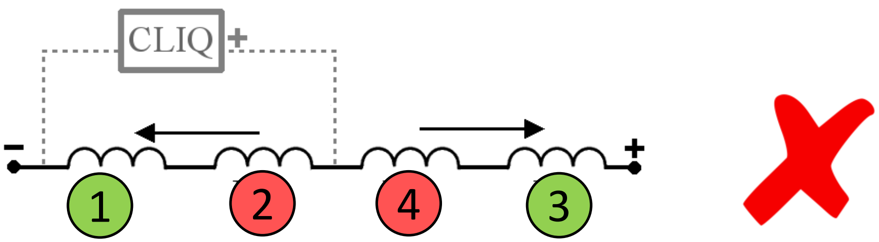
About 10 times **faster** heat deposition, AND **more uniform**

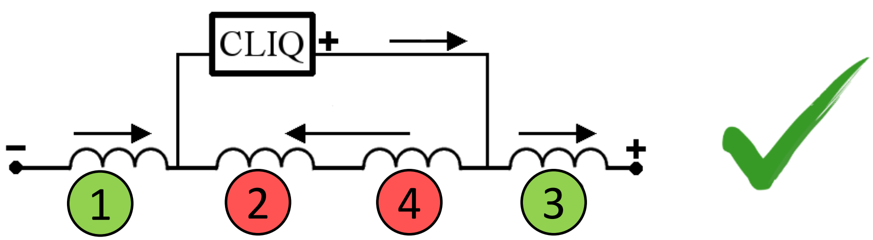
Is there a quick rule to determine whether a configuration is optimized?

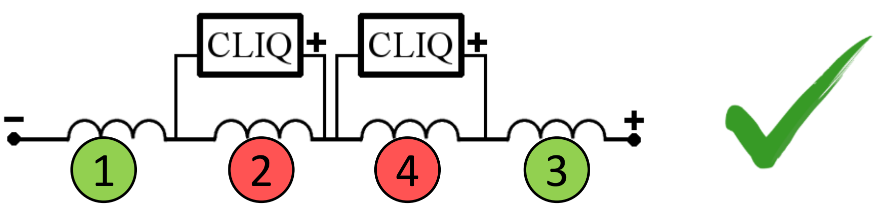
Indeed!

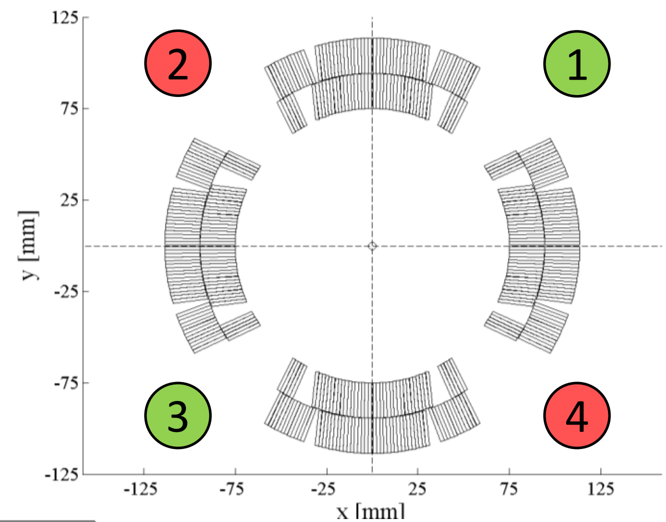
Poles that are physically adjacent must receive opposite dI/dt.

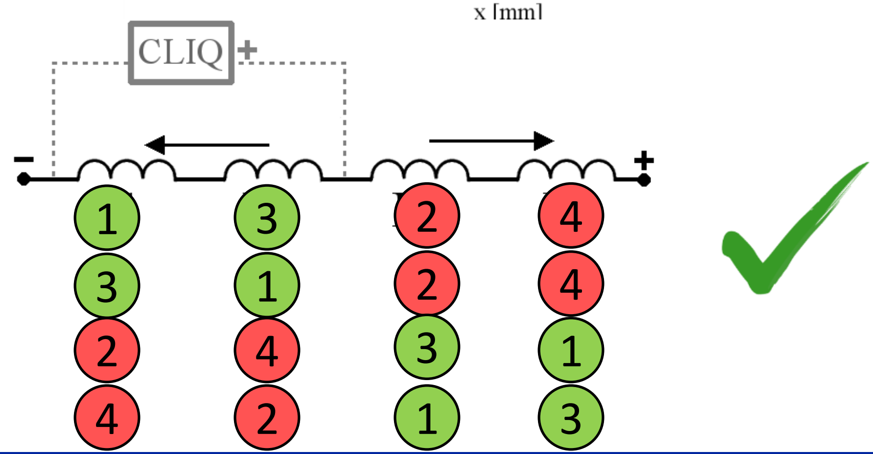
Some examples:











Wouldn't adding an EE system help?

- The addition of a 50 mΩ EE system decreases the hot-spot temperature only by a few degrees
- On the other hand, the peak voltage to ground is increased

4-CLIQ +OutQH	4-CLIQ +OutQH +EE	OutQH +EE
±500 V	1100 V	-800 V